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Measuring tree height: a quantitative comparison of two common field methods in a moist tropical forest

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Summary

1. Tree height is a key variable for estimating tree biomass and investigating tree life history, but it is difficult to measure in forests with tall, dense canopies and wide crowns. The traditional method, which we refer to as the 'tangent method', involves measuring horizontal distance to the tree and angles from horizontal to the top and base of the tree, while standing at a distance of perhaps one tree height or greater. Laser rangefinders enable an alternative method, which we refer to as the 'sine method'; it involves measuring the distances to the top and base of the tree, and the angles from horizontal to these, and can be carried out from under the tree or from some distance away.

2. We quantified systematic and random errors of these two methods as applied by five technicians to a size-stratified sample of 74 trees between 5.7 and 39.2 m tall in a Neotropical moist forest in Panama. We measured actual heights using towers adjacent to these trees.

3. The tangent method produced unbiased height estimates, but random error was high, and in 6 of the 370 measurements, heights were overestimated by more than 100%.

4. The sine method was faster to learn, displayed less variation in heights among technicians, and had lower random error, but resulted in systematic underestimation by 20% on average.

5. We recommend the sine method for most applications in tropical forests. However, its underestimation, which is likely to vary with forest and instrument type, must be corrected if actual heights are needed.

Key-words: Barro Colorado Island, Central America, clinometer, hypsometer, inclinometer, lowland forest, rain forest, tree stature

Introduction

Tree heights have long been measured as part of efforts to quantify timber resources (Avery & Burkhart 2011), and more recently also forest carbon stocks (Chave *et al.* 2005; Feldpausch *et al.* 2012). In addition, tree heights are often measured in ecological studies characterizing life histories of individual tree species and populations (King & Clark 2011; Banin *et al.* 2012). Typically, tree heights are reported together with equipment used, but without even a vague description of the methodology let alone discussion of potential biases.

A number of different methods are used to measure tree heights from the ground (Clark & Clark 2001; Chave 2005; CTFS 2007). Perhaps the simplest method involves lifting the top of a pole of known length to the same level as the top of the tree using, for example, a telescoping height measuring pole (or a telescoping fishing rod). This method is easy to learn but requires two field technicians because the relative height of the tops is difficult to judge from directly below. More importantly, this method is limited to relatively small trees (e.g. below 10 m in height). It is possible to apply a similar methodology to larger trees, but only by having a technician climb the tree (or an adjacent structure). This approach is used to measure potentially record-breaking trees (Goodwind 2004), but is obviously very slow and potentially dangerous, and thus not suitable for measuring large numbers of trees in inventories.

For larger trees, height measurements typically involve light, handheld instruments used to examine trees from a distance. Before laser rangefinders were easily available, the tangent method (Fig. 1) predominated. This method involves measuring angles (α and β in Fig. 1a) from horizontal with a clinometer and combining these with measurements of either horizontal distance or of angles to a pole of known length (Korning & Thomsen 1994). Historically horizontal distances were often measured with measuring tapes or simple distance prisms; more recently, ultrasound technology (e.g. Vertex IV by Haglöf) and laser rangefinders have been used for the same purpose. The advent of laser rangefinders made it possible to measure the distance to the top of the tree directly, and thus enabled measurements of tree height via the sine method (Fig. 1a). This method involves combining measurements of the distance to the top of the tree with angles from horizontal. For increased precision (reduced random error), both methods can also be implemented with a 'total station', for example, a

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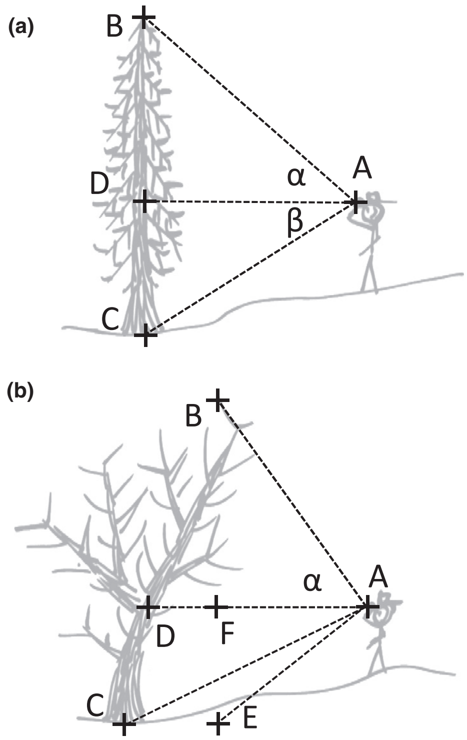

Fig. 1. Depiction of the tangent and sine methods of measuring the height of a vertical tree (a) and a leaning tree (b) from points A. Tree height or 'actual height' is defined as distance BC in (a) and BE in (b) in this article. For a vertical tree in which the top is directly above the trunk (a), the tangent method requires measuring angle α from horizontal to the top (B) and distance AD and computing BD = tan(α) · AD, where BD is the distance from B to D and AD the distance from A to D. If the ground is not flat and thus the vertical distance to the base, CD, cannot be easily estimated from the height of the technician, then CD can be estimated in the same way: CD = tan(β) · AD. The tree height is BC = BD + CD. The sine method is based on measuring the angle α and distance AB to the top of the tree and computing: BD = sin (α)· AB. As with the tangent method, CD can be estimated from the height of the technician alone on flat ground, or using the sine method. When the tree is leaning (b), or more generally when the topmost branch is not located above a vertical trunk, the tangent method risks severely biased estimates. For example, tan(α) · AD severely overestimates the height to the top of the tree in (b). Instead, this height is correctly estimated as tan(α) · AF, where AF is the distance to an imaginary plumb line hanging down from the top of the tree. Similarly, if the bottom part of the tree (below A) is also estimated with the tangent method, the angle needs to be measured to E which is at the same level with C but directly below B. In contrast, lean of the tree does not influence field procedures for the sine method as BF = sin(α)· AB and EF = sin(DAC) AC, where DAC is the angle between DA and AC.

theodolite with built-in laser technology to measure distances, but current models are heavy, and setting up such a heavy instrument on a tripod requires significantly more time.

The actual height measurement processes look superficially similar with the tangent and sine methods. Most of the measurement time is spent searching for a spot from which the top of the tree can be seen clearly. The main differences are that the sine method lacks the horizontal distance (AD in Fig. 1a) measurement and can be carried out from closer to the trunk (the precision of the tangent method declines quickly at higher angles and thus shorter distances). In addition, because the undergrowth often blocks the visibility to the base of the tree, technicians using the sine method often do not directly measure the vertical distance from the point of measurement to the base of the tree (CD in Fig. 1a), but instead estimate it based on terrain and their own height. In the simplest case, with flat ground and shooting directly up, a laser rangefinder can be used without a clinometer simply by adding the height of the technician to the vertical distance measured.

The sine and tangent methods both have specific requirements regarding visibility of the top of the tree, and these requirements differ in important ways. The sine method necessitates an unblocked path from the laser rangefinder to the top of the tree. The minimum width of the path depends on the laser technology, both in terms of the width of the laser beam and the detector settings for interpreting returns. Handheld laser rangefinders generally return only one distance from multiple objects in the line of sight, which can make it challenging to measure the top height of a dense crown, whose view is blocked from the sides by shorter trees. Many newer laser rangefinders, especially those designed for forestry, can also be set to return the distance based on the reflection from a more distant object – this is very useful for measuring height of canopy trees from directly under the canopy. Regardless, there must be some direct, unblocked path to the top of the tree in order for measurements to be taken using the sine method, and it can be difficult to find such a path in the dense and multi-layered canopies of tropical forests. In contrast, the use of the tangent method and a clinometer is capable of yielding good results even without visibility to the top. For example, if the crowns of the target species are normally symmetrical with the top in the middle and other parts of the crown can be seen, the technician can estimate the location of the top and measure the angle to it even if the top is not directly visible.

For the tangent method, the technician has to stand at a large enough distance that the angle from horizontal to the top remains fairly small. An oft-repeated recommendation is that this angle should be smaller than 45° (Goodwind 2004), which means that the observer stands at a distance equivalent to at least one tree height. The main reason for this recommendation is that the tangent of an angle increases very rapidly for larger angles, and thus, the precision of the height measurement declines disproportionately. In addition, the closer the observer is to the tree, the greater the bias if the tree is leaning or if the technician shoots not to the top directly above the base, but to parts of the crown closer to the technician. Especially in dense and tall forests such as many tropical forests, intervening vegetation often makes it difficult if not impossible to find a spot that has a sufficiently good view of the tree crown at a sufficiently large distance that the angle is <45 degrees. This contrasts with the sine method, in which the technician is free to make measurements at shorter distances to the tree, and even under the canopy. The specific visibility conditions of the forest will determine whether in practice it is easier to see where the top is from a distance greater than the tree height (tangent method) or to find an unblocked view of the top from anywhere (sine method).

Field ecologists and foresters have often discussed the best method and instrument to measure tree height and the scale of the uncertainty involved. For example, in a recent open peer review, the referee criticized the evaluated manuscript on tropical biomass estimation by stating 'Height could not and cannot be measured accurately in the field' (Saatchi 2012). The journal editor defended the authors by writing 'The authors are correct in stating that H can be measured accurately in the field' (Stoy 2012). These discussions reflect the fact that rigorous comparisons of field methods in natural tropical forests have been lacking.

Of the studies on uncertainty in tree height measurements that have been carried out, many focused on comparing instruments in ideal conditions of perfect visibility (Skovsgaard, Johannsen & Vanclay 1998; Wing, Solmie & Kellogg 2004). Based on these studies and our simple testing (Data S1), most instruments and both methods seem to have low systematic and random errors when measuring the height of a perfectly vertical tree with both top and bottom perfectly visible. However, these tests provide limited insight into the performance of these methods under typical measurement conditions in forests, with limited visibility and leaning trees. Other studies have described the risks involved in the tangent method, but these have either not included a comparison with the sine method (Goodwind 2004; Blozan 2006) or the comparison has lacked actual heights (Bragg 2008). We have located four studies in which researchers compared measurements from handheld instruments based on the tangent method with actual heights obtained by climbing: Rennie (1978) compared measured heights among six methods (that deviated from each other mainly on how AD in Fig. 1a is measured) and with actual heights; he found height measurements obtained using a simple clinometer and a measuring tape to be fast and relatively unbiased on easy to measure pines in a plantation. Similarly, Williams, Bechtold & LaBau (1994) compared measured heights among methods and with actual heights in another pine dominated research site with similar results. Da Silva *et al.* conducted two separate studies; one in a eucalypt plantation (da Silva *et al.* 2012a) and another in natural forest some 300 km northeast of Rio de Janeiro (da Silva *et al.* 2012b). In the plantation, mechanical clinometers performed better than electronic ones, and bias was significant only when distance to the tree was much smaller than tree height. In the natural forest, the random errors were larger, while bias remained unimportant. Surprisingly, simple visual estimation without any instruments performed as well or even better than the tangent implemented with the Haglöf Vertex (da Silva *et al.* 2012b). None of these studies included a comparison of measurements using the sine method.

Our objectives here are to quantify and compare total error, systematic error and random error of tree height measurements between the tangent and sine methods implemented with a laser rangefinder–clinometer in a moist neotropical forest. We quantify systematic and total error through comparisons with actual heights measured by climbing towers adjacent to the focal trees. Neotropical forests provide an especially challenging environment for ground-based tree height measurements because trunks are often leaning, crowns can be nearly as wide as the tree is high (King & Clark 2011; Primack & Corlett 2011) and visibility is limited due to the high leaf area index (Clark *et al.* 2008).

Materials and methods

This study was conducted in moist tropical forest on Barro Colorado Island in central Panama (9.16N, 79.85W). This site receives average annual rainfall of 2600 mm, with January, February and March receiving <100 mm (Leigh *et al.* 2004). The forest is semi-deciduous, with some species dropping their leaves during some or all of the dry season (Condit *et al.* 2000). The measurements were taken during July, August and September 2010, in the middle of the wet season, when nearly all living trees carried leaves.

At the time of our study, there were seven towers that extended above the canopy on Barro Colorado Island, all located at the tops of ridges or local high points, approximately 100 m above sea level. They were installed and maintained in a manner designed to minimize the impact on neighbouring trees: their concrete foundations and the towers themselves are <0.5 m in diameter, and each has sets of guy wires extending in 3 directions. The forests adjacent to the towers are mainly old secondary forest (80–120 years old), whose vertical structure and biomass are very similar to that of primary forest at this site (Mascaro *et al.* 2011). We sampled and marked all trees whose diameter was at least 3/100 times their distance to the centre of a tower, similarly as in a sample taken with a relascope (Avery & Burkhart 2011). Diameter was measured at 1.3 m or above buttresses. We chose the factor 3/100 to obtain a reasonable number of trees appropriately stratified by size, while avoiding problems with visibility of the top of the crown from the towers. We obtained a sample of 74 trees; heights ranged from 5.7 to 39.2 m, diameters from 52 to 2040 mm and distance from the tower centre from 1.2 to 34.1 m. (Data S2)

Tree height or 'actual height' is defined in this article as the vertical distance from the topmost living or dead part of the tree (including leaves) to the upslope side of the trunk base (where trunk and soil meet); hereafter referred to as the 'base of the tree'. The upslope side was used as the point of reference for tree height because this is the definition with which the technicians were familiar (Condit 1998), and despite the fact that this definition can lead to (small) decreases in height over time with increasing trunk diameter on slopes without actual changes in crown position. In the scientific literature, the term tree height has been used for both vertical (BE in Fig. 1b) and slope distance (BC in Fig. 1b). We chose to use vertical distance as it corresponds to remotely sensed forest height, is easier to quantify with handheld instruments for standing trees and is simpler to define in cases when the most distant shoot from the base is a tip of a branch and not the main stem. In contrast, the slope distance is a common choice in biomass studies on felled trees.

We used the Nikon Forestry 550 rangefinder–clinometer for all distance and angle measurements with its 'distant target mode' (see Data S1). Actual height of each tree was measured by climbing the adjacent tower. In each case, a technician climbed the tower to the point where the top of the tree was at eye level, as verified with the Ang mode of a Nikon Forestry 550 rangefinder–clinometer. The actual height was then obtained by hanging a measuring tape to the base of the tower and measuring the vertical distance from the base of the tower to the base of the tree with the same Nikon instrument. We estimate, based on difference between measurements by one of us

(Larjavaara) and technicians on sample trees, that our measurements of actual heights had errors of <0.2 m. Drastic errors due to measuring the wrong tree were in practice impossible as technicians were able to identify species based on both their bark and leaves, and neighbouring trees rarely belonged to the same species.

The tree height measurements using the tangent and sine methods were carried out by 5 technicians, each of whom measured all 74 trees with both methods. All five except technician 3 had extensive field experience with tree censuses in Barro Colorado Island, technicians 1 and 2 had recent experience with the sine method and technician 1 had months of experience with the tangent method but several year before. One of us (Larjavaara) taught both methods to technicians 1, 2 and 3, and technician 1 later taught the final two technicians under instructions to carry out similar training. The Nikon Forestry 550 rangefinder–clinometer was used for both methods. Initial tests showed that it has low error in open conditions (see Data S1 for details).

The training of the tangent method began in an open field, first with measurement of a vertical pole, then measurement of a vertical tree whose top was clearly visible, then trees whose tops were partially or fully obscured and/or not over the base, and finally moved to the forest, taking altogether several hours. Special attention was paid to train technicians to avoid the classic beginner's error of shooting too high up to branches on the side towards the technician. Technicians had to obtain good measurements (as assessed by the trainer) at each stage before moving on to the next stage. Technicians were instructed to go around the tree at a distance of approximately the height of the tree to try to find a spot from which the top was visible. If the top was not visible from any direction, they were to infer its location from what was visible. For trees not having their top directly above their base, we instructed them to imagine a plumb line hanging from the top to the same level as the base and to take angles and distances to this plumb line. The angles were measured with the Ang mode of the Nikon Forestry 550 rangefinder–clinometer and the horizontal distance to the middle of the trunk (or imaginary hanging plumb line) with the Act mode if possible. If it was not possible to directly measure this distance, then it was to be estimated based on measuring distance to other nearby objects and adding or subtracting appropriate offsets as necessary.

Similarly, the training of the sine method started with a vertical pole in an open field and ended with challenging trees in the forest. Technicians were told that they had two distinct options. The Nikon Forestry 550 has in addition to the Hgt mode that reports vertical distance (e.g. BF when shooting from A to B in Fig. 1b) the Hgt+Hgt2 mode that allows the user to shoot twice and reports the vertical distance between the targets (e.g. by shooting to B and C in Fig. 1b the device reports BE). The technicians were instructed to use the Hgt+Hgt2 mode when it was possible to find a point from which the top and base of the tree were both easily visible from over 10 m distance (the instrument cannot measure shorter distances), especially if the terrain was not flat. In other cases, they were instructed to use the Hgt mode for the distance to the top, to estimate the vertical distance from the device to the base of the tree and to add the two (or take the difference, if tree base was above the instrument on a steep slope). On flat terrain, the vertical distance from the device to the base of the tree is simply the height of the device from ground (e.g. 1.7 m, depending on height of the technician). On slopes, the vertical distance was estimated either by checking zero angle to the trunk and measuring the distance from that level to the base, or simply by rough visual estimation. As the sine method is rapid (especially when using Hgt mode), technicians were encouraged to repeat (up to twenty times) the measurement to different branches in the crown and potentially from different locations on the ground and record the highest.

It was made clear to technicians that the objective of the research was to compare methods and that all work should be conducted independently. To help insure that measurements with one method were not influenced by prior perceptions or by measurements with the other method, measurements for the sine method were carried out with the vertical height in a unit which the technicians had not used for tree height (feet, later converted to metres), and measurements with the tangent method were based on recording the two angles and the horizontal distance with no calculation of height carried out in the field.

We quantified total error, systematic error and random error for each method as applied by each technician, and for all technicians combined. We quantified total error with root mean squared error:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\Sigma(h_{\mathrm{meas},i} - h_{\mathrm{act},i})^2},$$

where $h_{\mathrm{meas},i}$ is the measured height of the i^{th} tree, $h_{\mathrm{act},i}$ is the actual height of the i^{th} tree and n is the number of trees. We quantified systematic error with the mean measurement error:

$$\mathrm{ErrMn} = \frac{1}{n}\Sigma(h_{\mathrm{meas},i} - h_{\mathrm{act},i}).$$

We quantified random error with the sample standard deviation of the measurement errors:

$$\mathrm{ErrSD} = \mathrm{SD}(h_{\mathrm{meas},i} - h_{\mathrm{act},i}) = \sqrt{\frac{1}{n-1}\sum\left(h_{\mathrm{meas},i} - h_{\mathrm{act},i} - \mathrm{ErrMn}\right)^2}.$$

Because errors increased with the true height, we also calculated all of the above in proportional terms. Specifically, proportional root mean squared error was calculated as

$$\mathrm{RMSE}_{\mathrm{prop}} = \sqrt{\frac{1}{n}\Sigma\left(\frac{h_{\mathrm{meas},i} - h_{\mathrm{act},i}}{h_{\mathrm{act},i}}\right)^2},$$

proportional systematic error as

$$\mathrm{ErrMn}_{\mathrm{prop}} = \frac{1}{n}\Sigma\left(\frac{h_{\mathrm{meas},i} - h_{\mathrm{act},i}}{h_{\mathrm{act},i}}\right)$$

and proportional random error as

$$\mathrm{ErrSD}_{\mathrm{prop}} = \mathrm{SD}\left(\frac{h_{\mathrm{meas},i} - h_{\mathrm{act},i}}{h_{\mathrm{act},i}}\right) = \sqrt{\frac{1}{n-1}\sum\left(\frac{h_{\mathrm{meas},i} - h_{\mathrm{act},i}}{h_{\mathrm{act},i}} - \mathrm{ErrMn}_{\mathrm{prop}}\right)^2};$$

these were reported in percentages. We will refer to a measurement method as biased if its mean error is significantly different from zero. We note that in general, higher precision is defined by lower random error, and higher accuracy is variously defined as lower systematic error or lower total error. Here, we generally avoid these potentially confusing terms in favour of direct statements about total, systematic and random error.

We fitted power and linear regressions for actual height as a function of measured height for each of the 12 data sets (2 methods, 5 technicians including fitting with all technicians combined), fitted as $h_{\mathrm{act}} = a + b\ h_{\mathrm{meas}}$ and $\log(h_{\mathrm{act}}) = a + b\log(h_{\mathrm{meas}})$. For each data set and model combination, we calculated RMSE for actual heights relative to heights estimated from the measurements using the models. When predicting untransformed heights (and assessing their RMSE) from the power function model, we applied the standard correction factor: $h_{\mathrm{act}} = ch^b_{\mathrm{meas}}$, where $c = \exp\left(a + \frac{\mathrm{RSE}^2}{2}\right)$, and RSE is the residual standard error of the log-log regression (Chave *et al.* 2005). In addition, we computed Pearson correlation coefficients.

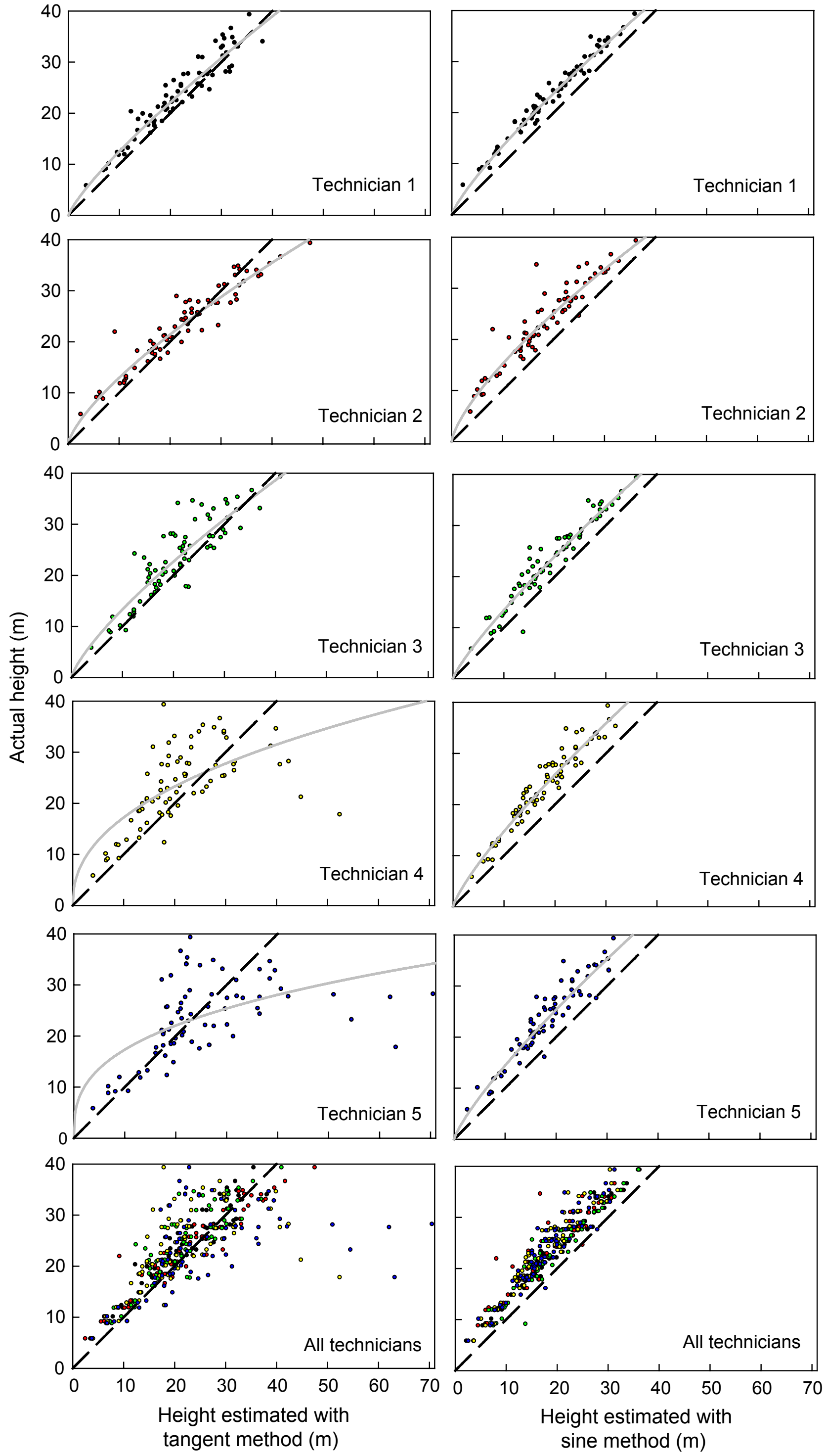

Fig. 2. Actual (or true) tree heights relative to heights measured using the tangent method (panels on the left) and sine method (panels on the right). The top five rows show the data for individual technicians; the bottom row shows data for all technicians combined. Solid curves show the power models and dashed lines the 1 : 1 lines.

Results

Training in the tangent method took approximately twice as long as training with the sine method, because it took longer to reach sufficient agreement with the trainer's measurements on the training examples. The principles of the tangent method are easy to learn; the difficulty is in applying these methods to trees whose crowns are not directly above their trunks, as this requires a good understanding of this trigonometric method and three-dimensional visualization skills. The time to measure trees was also somewhat longer for the tangent method. This time was recorded for one technician for 18 nearby trees, and the total time was 14% longer with the tangent method (45.0 vs. 39.5 min).

Heights measured using the tangent method were on average close to and centred around the 1 : 1 line, but with fairly large scatter (Fig. 2). There were several cases of severe overestimation of the heights by more than 100% (Fig. 2, technicians 4 and 5). In all six or 1.6% of the cases, these severe overestimations were associated with angles of over 70° (α in Fig. 1) when shooting to the top. This initially suggested that the problem was caused by the technician standing too close to the tree or imagined plumb line. However, back calculation of what the angle should have been to obtain the actual height given the measured horizontal distance showed that the correct angle was not overly wide (and the technician was not overly close), assuming the measured distance from the tree was the actual distance. Thus, it appears that the real problem was that the technician shot too high up from a typical distance, probably due to difficulty in figuring out what part of the crown was directly over the base.

Heights measured using the sine method showed less scatter and were nearly all underestimates. This systematic underestimation is not surprising, as the topmost branch or leaf is difficult to locate and may be obscured. All five technicians had a similar pattern, with few major outliers (Fig. 2b,d,f,h,j). Technicians were allowed to choose between the Hgt+Hgt2 mode, in which visibility to the base was needed, and the Hgt mode. The Hgt+Hgt2 mode was chosen by technician 1 for 11 trees, by 2 for 6 trees, by 3 for 19 trees, by 4 for 17 trees and by 5 for all 74 trees. The underestimations with the Hgt+Hgt2 mode were less severe, but we suspect this is simply because it was used with trees that are easier to measure and not because it is a superior method.

These observable differences between the methods (Fig. 2) are quantified in differences in their errors (Table 1). The tangent method exhibited less systematic error than the sine method for every technician and all technicians combined (all technicians combined: ErrMn -0.76 vs. -4.50 m, and $ErrMn_{prop}$ -3.4 vs. -20.5%). On the other hand, the sine method had less random error for every technician and for all technicians combined (all technicians combined: ErrSD 2.31 vs. 6.82 m, and $ErrSD_{prop}$ 10.8 vs. 29.6%). The lower random error of the sine method made it a better predictor of true height, with higher correlation coefficients for 4 of 5 technicians and for all technicians combined both for untransformed and log-transformed height. Total error was lower for the sine method for all technicians combined (RMSE 5.05 vs. 6.85 m, and $RMSE_{prop}$ 23.2 vs. 29.7%), with split results among technicians. RMSE was lower for the sine method for 3 of 5 technicians, while $RMSE_{prop}$ was lower for the sine method for only 2 of 5 technicians (Table 1).

The power function model performed slightly better than the linear model, exhibiting lower RMSE (Table 2). RMSE for model-predicted heights was lower for the sine method overall and for 4 of 5 technicians. The fitted model parameters were quite similar among technicians for the sine method, but differed strongly and significantly for the tangent method, indicating greater differences among technicians for the tangent method. The sine method measurements were more strongly correlated with actual tree height (r_{lin} = 0.95 vs. 0.71, r_{log} = 0.96 vs. 0.86) overall and for 4 of 5 technicians, both for untransformed and log-transformed heights.

Discussion

The results show clear differences between the methods. Measurements with the tangent method had little systematic error but high random error, systematic differences among technicians and occasional large errors for some technicians. The sine method was faster to learn, its results were more repeatable across technicians, and in general, it exhibited lower random error – but it had high systematic error, consistently underestimating heights. Surprisingly, even heights of small trees were systematically underestimated by the sine method, perhaps because technicians accidentally

Table 1. Summary statistics of errors in measured tree heights for different measurement methods and technicians, in both absolute and proportional terms, along with Pearson correlation coefficients for untransformed (r_{lin}) and log-transformed heights (r_{log})

		Total error		Systematic error		Random error		Correlation coefficients	
	Technician	RMSE (m)	$RMSE_{prop}$ (%)	ErrMn (m)	$ErrMn_{prop}$ (%)	ErrSD (m)	$ErrSD_{prop}$ (%)	r_{lin}	r_{log}
Tangent method	1	**2.88**	**13.4**	**−1.66**	**−8.38**	2.37	10.6	0.95	0.97
	2	**3.19**	**15.8**	**−0.26**	**−3.89**	3.20	15.4	**0.95**	**0.96**
	3	4.31	**17.4**	**−2.20**	**−9.05**	3.74	15.0	0.88	0.91
	4	8.12	35.9	**−1.94**	**−6.95**	7.94	35.5	0.58	0.78
	5	11.48	49.0	**2.25**	**11.35**	11.33	48.0	0.46	0.72
	Combined	6.85	29.7	**−0.76**	**−3.38**	6.82	29.6	0.71	0.86
Sine method	1	3.71	19.3	−3.52	−17.08	**1.19**	**8.9**	**0.99**	**0.99**
	2	5.49	25.4	−4.81	−22.41	**2.68**	**12.1**	0.94	0.95
	3	**4.26**	20.4	−3.73	−16.45	**2.07**	**12.1**	**0.96**	**0.95**
	4	**5.85**	**25.5**	−5.43	−24.20	**2.21**	**8.1**	**0.96**	**0.97**
	5	**5.60**	**24.5**	−5.01	−22.29	**2.51**	**10.2**	**0.95**	**0.96**
	Combined	**5.05**	**23.2**	−4.50	−20.49	**2.31**	**10.8**	**0.95**	**0.96**

Bold highlights the better values in paired comparisons between the tangent and sine measurement methods.

Table 2. Parameters (with 95% confidence intervals) and RMSE for power function models ($h_{act} = ch_{meas}^{b}$) and for linear models ($h_{act} = a + b\ h_{meas}$) relating measured tree heights. Pearson correlation coefficients for untransformed (r_{lin}) and log-transformed heights (r_{log})

		Power function model			Linear model		
	Technician	*c*	*b*	RMSE (m)	*a*	*b*	RMSE (m)
Tangent method	1	1.83 (1.59, 2.10)	0.83 (0.78, 0.88)	2.21	3.59 (2.07, 5.12)	0.91 (0.84, 0.98)	2.25
	2	2.55 (2.19, 2.97)	0.71 (0.66, 0.76)	**2.26**	5.65 (4.22, 7.08)	0.77 (0.71, 0.82)	**2.32**
	3	1.75 (1.34, 2.29)	0.85 (0.76, 0.94)	3.58	4.73 (2.23, 7.22)	0.88 (0.77, 0.99)	3.60
	4	3.38 (2.36, 4.85)	0.64 (0.52, 0.76)	6.10	13.37 (9.80, 16.93)	0.47 (0.31, 0.62)	6.14
	5	4.02 (2.72, 5.94)	0.55 (0.43, 0.68)	6.66	16.24 (12.76, 19.72)	0.28 (0.16, 0.40)	6.64
	Combined	2.74 (2.41, 3.13)	0.69 (0.65, 0.74)	5.14	10.84 (9.46, 12.22)	0.55 (0.50, 0.61)	5.29
Sine method	1	2.28 (2.09, 2.50)	0.78 (0.75, 0.81)	**1.21**	3.66 (2.88, 4.43)	0.99 (0.96, 1.03)	**1.18**
	2	2.71 (2.30, 3.19)	0.74 (0.69, 0.80)	2.59	5.64 (3.98, 7.29)	0.96 (0.87, 1.04)	2.64
	3	1.83 (1.52, 2.21)	0.86 (0.79, 0.92)	**2.03**	3.36 (1.97, 4.76)	1.02 (0.95, 1.09)	**2.05**
	4	1.98 (1.73, 2.27)	0.86 (0.81, 0.91)	**2.05**	3.77 (2.36, 5.17)	1.09 (1.02, 1.17)	**2.11**
	5	2.17 (1.84, 2.55)	0.82 (0.76, 0.88)	**2.39**	3.72 (2.06, 5.39)	1.07 (0.98, 1.16)	**2.45**
	Combined	2.24 (2.09, 2.41)	0.80 (0.78, 0.83)	**2.25**	4.31 (3.64, 4.98)	1.01 (0.98, 1.04)	**2.30**

Bold highlights the better values in paired comparisons between the tangent and sine measurement methods.

targeted lower parts of the crowns, especially if the view to the top was blocked.

The differences among the methods imply that each method should be preferred in certain circumstances. When measured heights are assumed to correspond to actual heights and data are abundant, minimizing the systematic error is usually most important, and thus, the tangent method is preferred. The tangent method had less systematic error for every technician and overall (albeit results varied among technicians), while the sine method showed systematic error for every technician. In terms of RMSE relative to the 1 : 1 model, the sine method did somewhat better overall, and for 3 of 5 technicians, including big improvements in the case of technicians 4 and 5 (who made some large errors with the tangent method). When measured heights are used as indicators of tree height without being assumed identical to actual heights, or when measured heights can be statistically corrected to obtain estimated actual heights, then the best method minimizes the RMSE of fitted models relating measured and actual heights, criteria that favour the sine method. The sine method performed much better than the tangent method by these metrics, both overall and for four of five technicians (the sole exception was technician 2, who did very slightly better with the tangent method).

The main disadvantage of the tangent method is the higher probability of major errors, and more random error in general. This method can produce good results when used carefully [e.g. Fig. 2, technicians 1–3 and (da Silva *et al.* 2012b)], but requires careful training and consistently conscientious application. Two of the five technicians obtained very poor data with the tangent method, with multiple cases of severe overestimation of height (Fig 2g,i). This cautions against the use of the tangent method unless one can be fairly sure to avoid such errors. In practice, training by testing against actual heights is often impractical as these are difficult to obtain. Probably, the best method is to compare measurements of a reliable trainer to the measurements of the trainees and extend training until the trainees consistently obtain similar heights to the trainer even for the most challenging trees. The tangent method is very sensitive to the training given, and improved guidance would surely have improved its performance.

The main disadvantage of the sine method is its systematic underestimation of tree heights. Underestimation was found for all size classes of trees and for all technicians, with sine measured heights on average just 80% of the true height in our data set (Fig. 2, Table 1). Therefore, height measured based on the sine method should not be assumed identical to actual heights. The heights measured with this method can either (1) be corrected based on fitted models (such as those in Table 1) to obtain unbiased estimates of actual height or (2) be used without correction with the caveat that these are biased measurements, a fact that might be emphasized by referring to them as 'nominal heights'. It is likely that the relationship between nominal and actual heights will vary among forests and potentially among tree species and seasons depending on forest structure, deciduousness at the time of measurement, leaf area index, crown shape, etc. The relationship between nominal and actual heights might also vary among models of laser rangefinder, as it is likely to depend on the laser beam divergence (and thus width when it hits the target), and the proportion of reflection based on which the distance is computed, and detector settings more generally, including technical specifications which may be proprietary and which may change over time as new models replace older ones (the performance of Nikon Forestry 550 is discussed in Data S1). It is possible that forest type and laser technology–specific correction functions will be developed, but this would require much additional research in this field. Even these sophisticated functions would not capture variation among technicians. Thus, total avoidance of systematic errors in height measurements obtained using the sine method would require fitting project-specific models, which in turn requires having unbiased height measurements for a subset of trees. Alternatively, if these nominal heights are measured similarly in multiple projects, among-site comparisons and other analyses could be based on nominal rather than actual heights. Indeed, it is possible that nominal heights might represent tree size better than actual heights (and thus be more biologically meaningful), because nominal heights are likely to reflect the height of the upper leaf layers of the main crown, while actual heights reflect the height to the uppermost twig. However, comparisons of nominal heights among projects and over time may be compromised if instrumentation effects prove substantial, and nominal heights should not be substituted for actual heights in biomass equations based on height measured on felled trees.

Conclusions and recommendations

Given the differences we observed in the performance of the two methods, it is critically important that ecological papers reporting or using tree height data state the method used to measure tree height. It would further be useful if they stated the experience and training of the technicians and the approximate time spent per tree. Papers using height data to estimate tree carbon stocks could account for uncertainty and potentially bias in tree height estimation (Feldpausch *et al.* 2012; Molto, Rossi & Blanc 2012). In both research fields, tropical tree height measurements should preferably be carried out by skilled, motivated and experienced technicians whose performance is tested regularly.

Overall, we recommend the sine method in most cases because it is less prone to major errors, shows more consistent performance across technicians and is faster to learn and implement (see Data S3 for a recommended protocol). However, it is important to keep in mind that sine method measurements consistently underestimate actual heights and that this underestimation may vary with instrumentation, forest structure and time spent per tree. Where data on actual heights are needed, we recommend careful application of the tangent method, or calibration of sine measurements against actual heights or unbiased measurements thereof. We also recommend the tangent method for small trees that are overtopped by other trees (if a pole cannot be used). Collection of good data with the tangent method requires a generous amount of high quality training, optimally with trees of known height and consistently conscientious application in the field. The tangent method is especially problematic when the objective is to find the tallest tree as shooting to the nearer part of the crown can lead to drastic overestimation (Goodwind 2004; Bragg 2008). The sine method, on the other hand, is excellent for measuring record-breaking trees of canopy species, as with plenty of time underestimation of height can be minimized and overestimation is in practice impossible except on steep slopes (Goodwind 2004; Bragg 2008).

Future methodological studies should further evaluate how the systematic error in the sine method varies among forests differing in structure, and among instruments differing in specifications, to develop a better basis for estimating actual heights from these measurements. It would be particularly interesting to evaluate the generality of our surprising finding that the sine method substantially underestimates the heights of short trees. This could easily be carried out through comparisons with true heights measured with telescoping poles.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Data S1. Nikon Forestry 550 - Testing and comments

Data S2. Main data set

Data S3. Suggested protocol based on the sine method