Supplementary material for article "Tropical tree biomass equations from terrestrial LiDAR: A case study in Guyana"

S.1 Field protocol summary

1. Measure preharvest

   - Mark coordinates, label tree
   - Measure: diameter (paint location), total height (H_{tot}), crown radius
   - Note: crown quality, structural damage, stem irregularities

2. Post-felling measurements

   - Remeasure tree size
     - Re-measure: diameter (same location), total height (H_{tot}), crown radius
     - Measure: H_{tot}, stump height (H_{stump}), commercial height (H_{com}), height of first major branch (≥ 5 cm; H_{FMB})
   - Separate and weigh
     - Small branches (<10 cm diameter)
     - Large branches (≥ 10 cm diameter)
     - Commercial bole
     - Non-commercial bole
     - Stump
   - Take wood samples
     - Label each sample and measure fresh mass
       * Small branches (Bs)
       * Large branches (BL)
       * Trunk (T)
       * Stump (St)
     - Measure volume as soon as possible
     - Store samples in the sun, if possible
     - Transport samples to laboratory, dry, and weigh

S.2 TLS data acquisition and Plot sampling design

S.2.1 TLS data acquisition

This LiDAR scanner is a discrete multiple-return laser scanner and its specifications are detailed in the following table. We set up two (virtual) rings around each tree to be scanned: an inner ring at 6 m from the trunk and an outer ring at 14 m from the trunk. We set up 8 to 10 scan positions between the inner ring and outer ring.

Terrestrial laser scanning RIEGL VZ-400 specifications for wavelength, beam divergence scan range and scan resolution.

Wavelength	1550 nm
Beam divergence	0.35 mrad
Scan range	360° in azimuth
	100° in zenith
Scan resolution	0.04 degree

S.2.2 TLS acquisition protocol

1. Plot delineation.

    - Find tree, label tree.

2. Plot set up

    - Set up inner and outer ring of 8 scan positions.
    - Set up reflector sets + 3 reflectors for tilt.
    - Clean up area low vegetation occluding reflectors view (1 m to 2 m height along the view lines from scan positions to reflectors).
    - Note on field sheet data.

3. GPS

    - Turn on GPS.
    - Save name of position in GPS and field sheet.
    - Save averaged measurements (leave it running, save it at the end before going to new scan position).

4. TLS scanning

    - Set up tripod where the scan position was determined.
    - Set up TLS and plug battery.
    - Find north and orient TLS in Y-axis towards the target tree.
    - Fill field sheet (orientation, position number, tripod height, GPS code).
    - Turn on TLS.
    - Scan on upright position.
    - Scan on tilt position.
    - Turn off TLS.
    - Remove TLS from tripod and take it to next scan position.

5. Start again from point 2.

6. Download and backup TLS data

    - Connect TLS to power and to laptop.
    - Copy data to two 2 external hard drives.
    - Delete scans from TLS.

S.2.3 Plot set up and scanning progression within the plot

Once we found the tree, we label the tree (see Figure S.2.3.1). We set up a total of eight scan positions, four in an inner ring at 6 m from the tree and the other four at 14 m from the tree. We cleared the surrounding vegetation and check that the tree can be clearly seen (specially the crown) at every position.
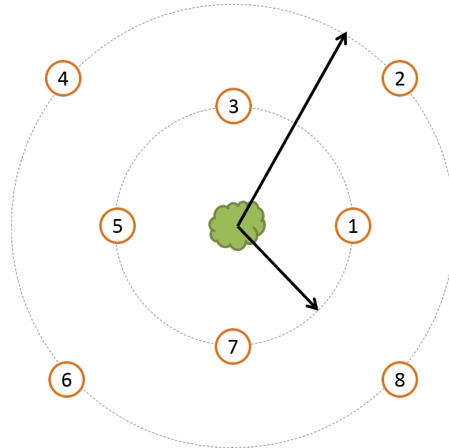

Figure S.2.3.1

This is the direction that we will follow from the tree (see Figure S.2.3.2). Choose one point and scan counter-clockwise.
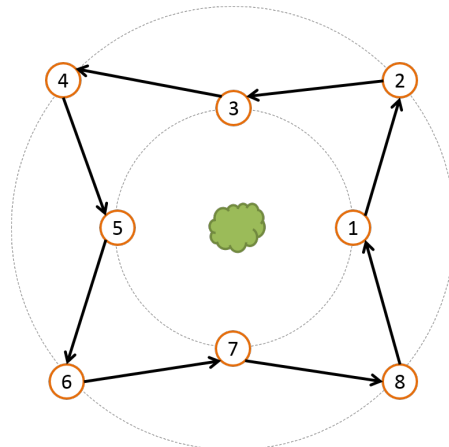

Figure S.2.3.2

For the first scan, we set up three sets of reflectors: A, B and C (Figure S.2.3.3, left). We must be careful enough that each set of reflectors is being seen by the other scan position. For example, Set of reflector A has to be seen from scan position 1 and 2. Once the scan finished, we moved to scan position 2 (Figure S.2.3.3, right). We set up reflector set D and can this position. Then, we move to scan position 3 (Figure S.2.3.4, left) and move reflector set A and E. We continue following this pattern until we finished the plot (Figure S.2.3.5 and S.2.3.6).
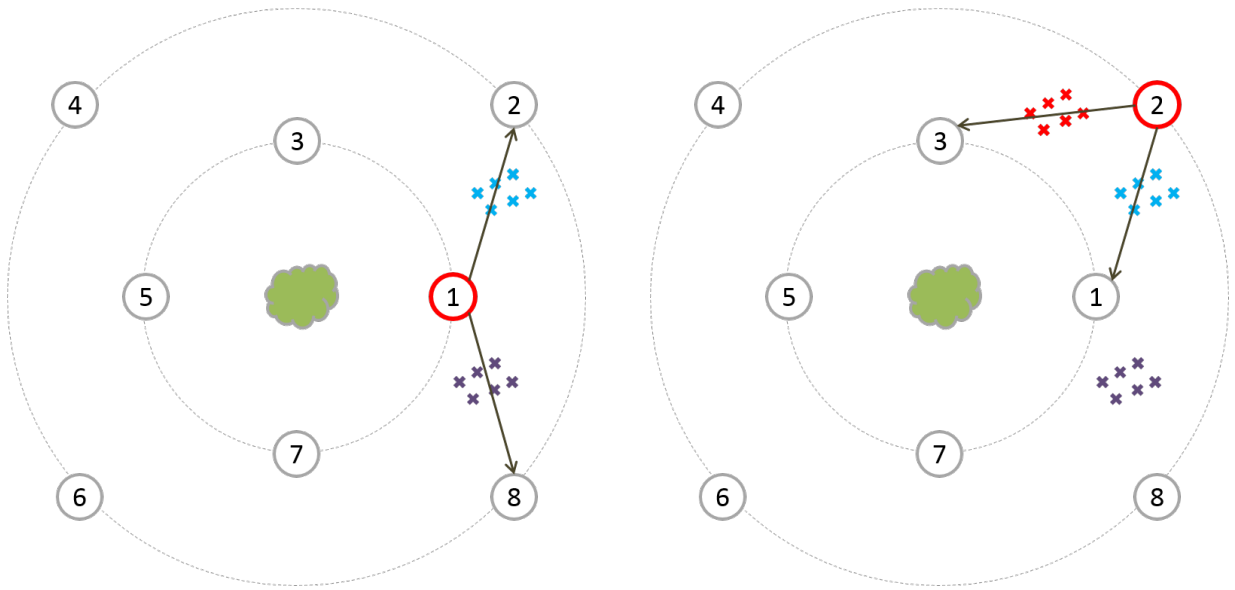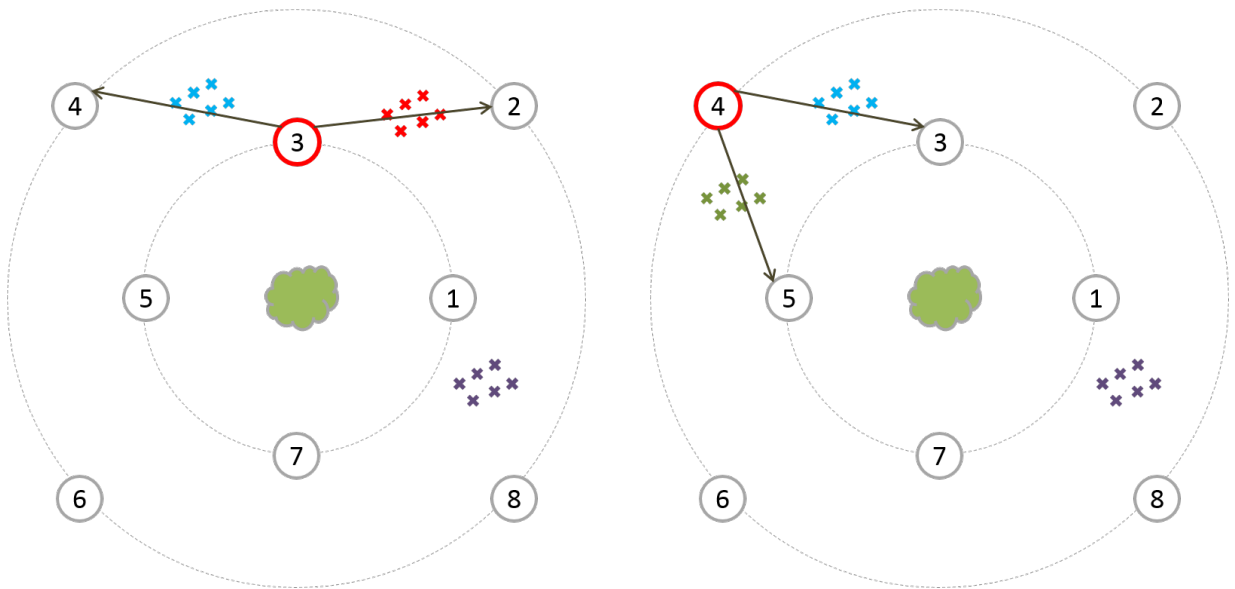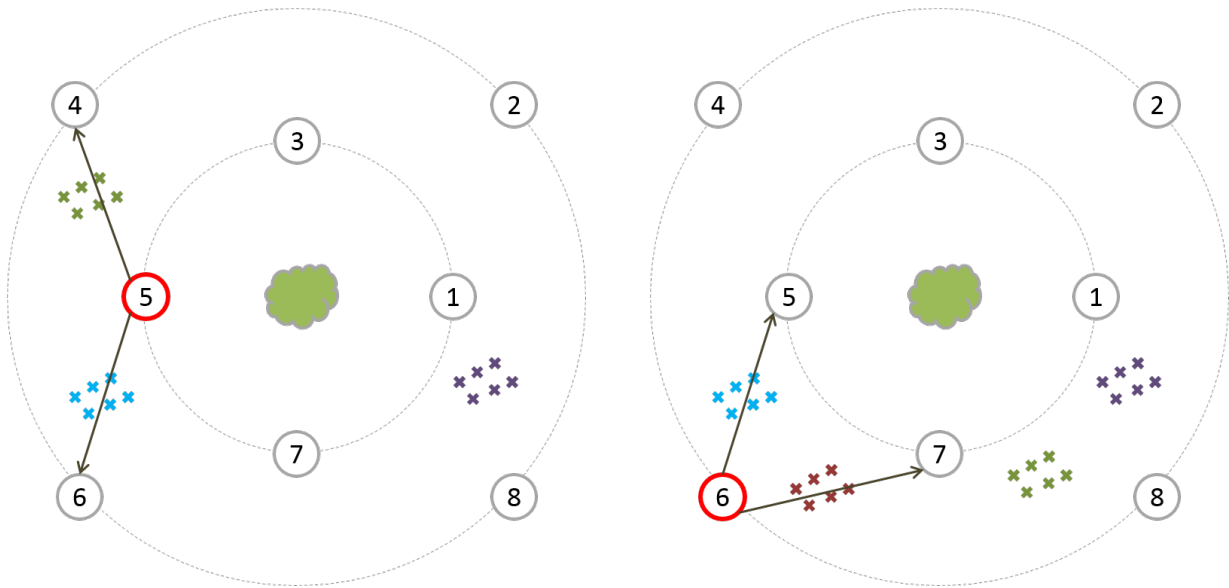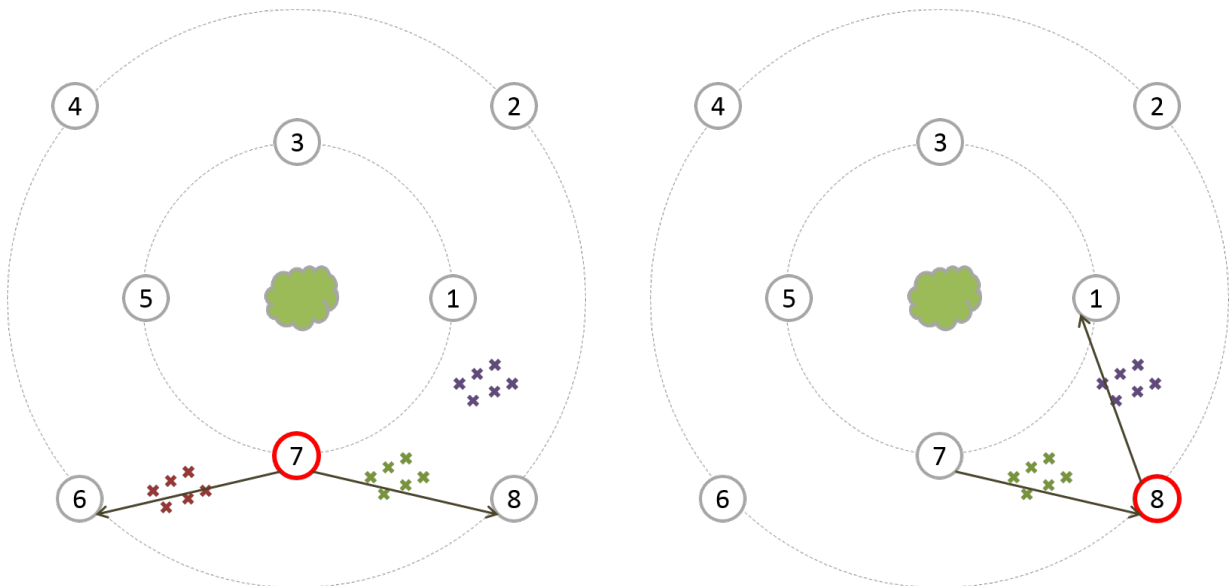
Figure S.2.3.3

Figure S.2.3.4

Figure S.2.3.5

Figure S.2.3.6

S.2.4   Download data and backup

For each tree, create a folder with the treeID and we copy the number of scans (minimum 16 scans).
Transcribe the field sheet into a word file with the same name of the tree.
Download the GPS data and save it with the treeID.
Download camera pictures and save them in a folder.
After downloading, create copies in external hard drives.

S.3 Laboratory work

1. Label samples. In field, label all pieces of the wood samples. Bark may fall off while air drying, so label the bark as well and/or put in a labelled paper bag.

2. Volume of samples.

   - We separated and weighed each tree into the following parts: small branches ($< 10\,\text{cm}$ diameter, including leaves), large branches ($\geq 10\,\text{cm}$ diameter), bole (stump to first branch), and stump.
   - Fresh mass was measured directly in field with a 300-kg capacity digital scale with $0.1\,\text{kg}$ precision. All irregular boles and boles of $D < 70\,\text{cm}$ were weighed directly. Larger and non-irregular stems and very large branches were measured through volume estimation (diameter every $1\,\text{m}$). We measured length, top diameter, and bottom diameter of any hollow sections.
   - Measure by displacement: "Accurate water displacement requires immersion of the wood sample into a beaker of water loaded on a top-loading electronic balance. The wood sample is pressed below the water surface with the aid of a "volumeless" needle or insect pin. The volume of the wood is read accurately on the balance as the mass of the displaced water. Older methods of volume displacement in graduated cylinders or beakers where water levels are read by sight are much less accurate and increase variance in volume measurements" (Williamson and Wiemann, 2010).

3. Oven dry samples.

   - Wood samples at $101\,°\text{C}$ to $105\,°\text{C}$.
   - Foliar, fruit, and flowers at $60\,°\text{C}$ to $70\,°\text{C}$ (Williamson and Wiemann, 2010).
   - Dry to constant mass

4. Dry Weight.

   - Remove samples from oven
   - Cool in box with desiccant

5. Save samples.

   - Dry sub-samples will be prepared and stored for analysis of carbon concentration. Sampling will depend on variability of carbon contents, time, and financial resources.

We calculated tree dry mass by two methods: (i) for tree parts which had been directly measured, we calculated dry mass by multiplying fresh mass by dry mass fraction (dmf), and (ii) for tree parts which had been measured by volume, dry mass was calculated by multiplying volume (minus hollow sections) by WD. We added the estimates from both methods for each tree part and then the complete tree.

References

Vicari, M.
  2017. TLSeparation.

Wilkes, P., A. Lau, M. Disney, K. Calders, A. Burt, J. Gonzalez de Tanago, H. Bartholomeus, B. Brede, and M. Herold
  2017. Data acquisition considerations for Terrestrial Laser Scanning of forest plots. *Remote Sensing of Environment*, 196:140–153.

Williamson, G. B. and M. C. Wiemann
  2010. Measuring wood specific gravity...correctly. *American Journal of Botany*, 97(3):519–524.

S.4   Semi-automated extraction of individual trees from TLS plots

A framework was designed to semi-automated extract individual tree from TLS plots:

a) We co-registered each scan using RiScan Pro Software [RIEGL Laser Measurement Systems GmbH, Horn, Austria, `www.riegl.com`, version 2.5.1] with a registration accuracy below $1\,\text{cm}$ (Wilkes et al., 2017). We kept the co-registration files and the individual files as input for the algorithm.

b) For each tree, we extracted a small cross-sectional point cloud. This cross section specifies the location of the tree to the algorithm.

c) The algorithm locates the tree from the ring and creates a point cloud subset which contained the potential tree.

d) We manually cleaned the tree point cloud subset from other features present (such as lianas, stems and canopies from other trees). In addition, we ensure that no branches or canopy parts are missing in the subset. If parts were missing, we manually extracted them from the initial point cloud.

e) Individual trees are down-sampled to a minimum of 1 point per $26\,\text{mm}^3$ to create a uniform point density throughout the whole tree.

f) Finally, material separation algorithm separated hardwood (stem and branches) from soft tissues (leaves) on our down-sampled trees (Vicari, 2017).

S.5   Tree point cloud dataset

Tree point clouds of the TLS dataset by diameter size class and coloured by height. Tree dataset comprises 72 TLS scanned trees and 26 harvested trees from 48 different species in 24 different families with diameter ranging from 12.9 cm to 149.8 cm and heights ranging from 6.33 m to 49.2 m.

Diameter size class
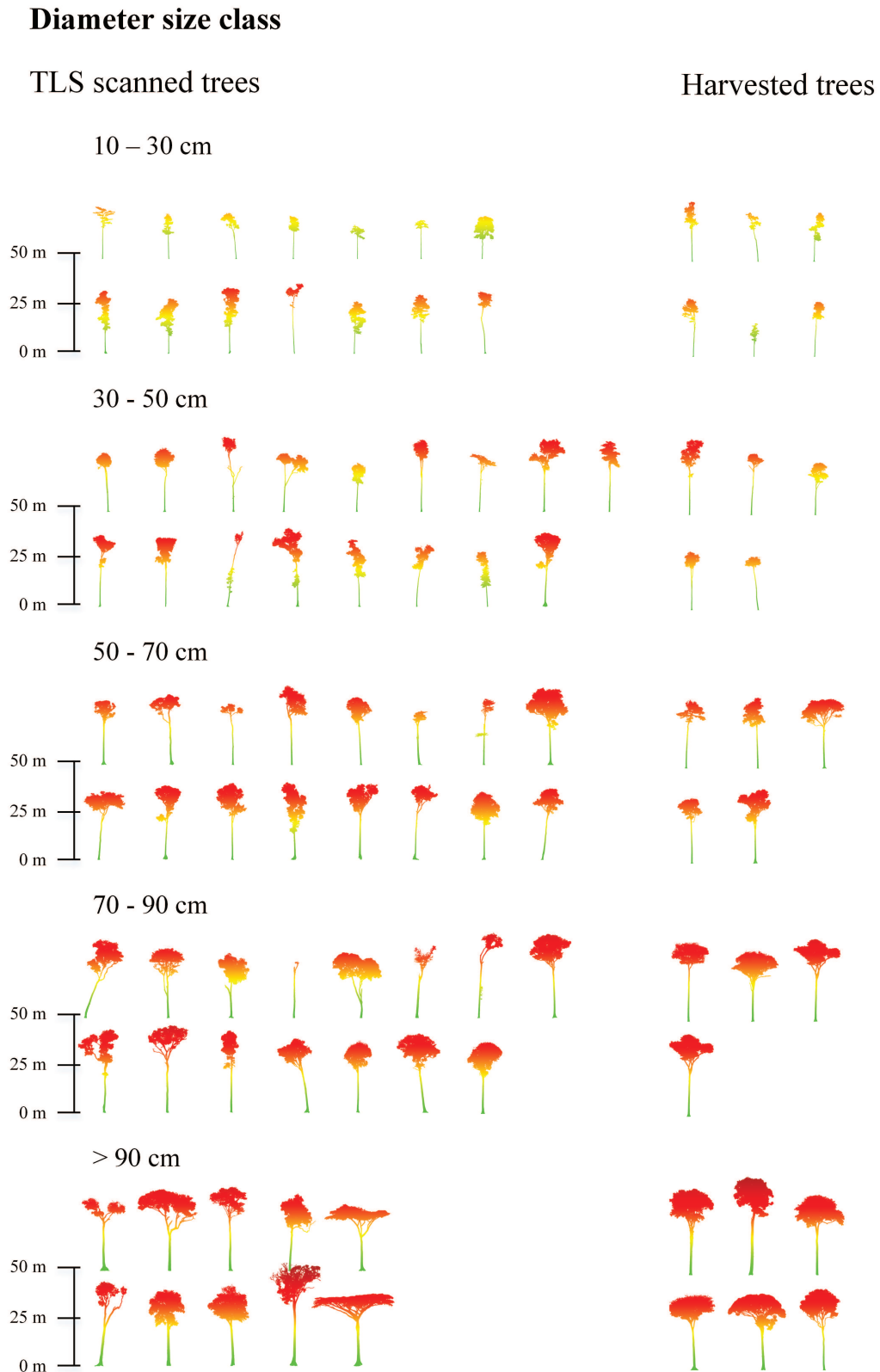
S.6 Wood density values for field inventory and destructive sampling

Wood density from field inventory (GWDD) and destructive sampling (weighted) from 72 and 26 trees respectively.

Diameter class (cm)	Field inventory ($n = 72$)				Destructive sampling ($n = 26$)			
	n	min	max	mean	n	min	max	mean
$10 \leq \text{DBH} < 30$	14	0.520	0.971	0.756	6	0.561	0.836	0.711
$30 \leq \text{DBH} < 50$	17	0.378	0.971	0.777	5	0.384	0.908	0.634
$50 \leq \text{DBH} < 70$	16	0.484	0.971	0.760	6	0.421	0.857	0.713
$70 \leq \text{DBH} < 90$	15	0.524	0.862	0.733	4	0.627	0.852	0.706
$\text{DBH} \geq 90$	10	0.390	0.862	0.627	5	0.408	0.808	0.635

S.7 Residuals vs fitted and Q-Q plots for models m4 and m5

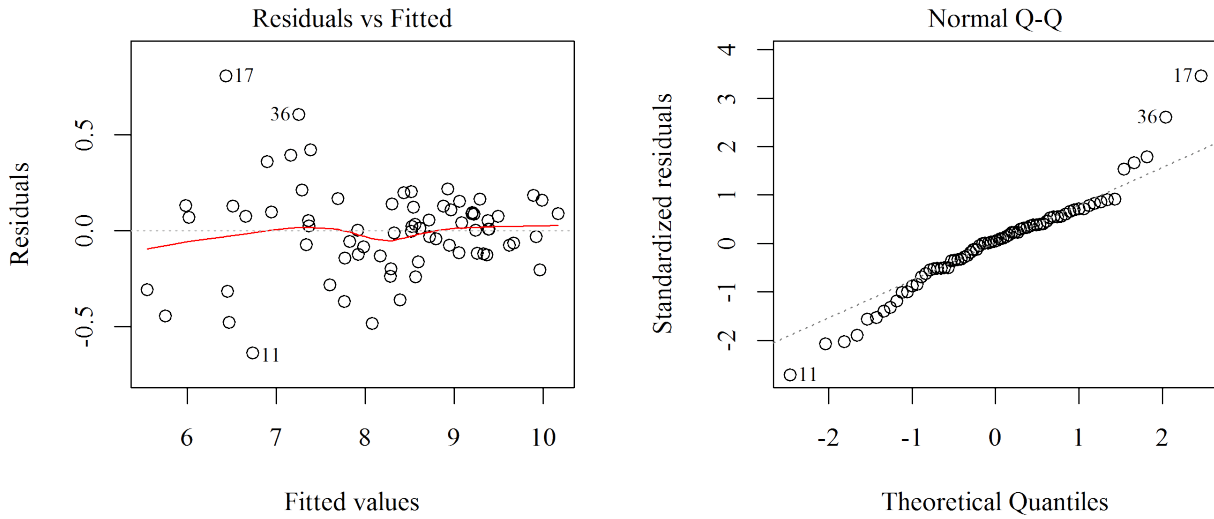TLS-derived allometric model m4 (top) and m5 (bottom) residual vs fitted (left) and Q-Q plots (right) graphs.
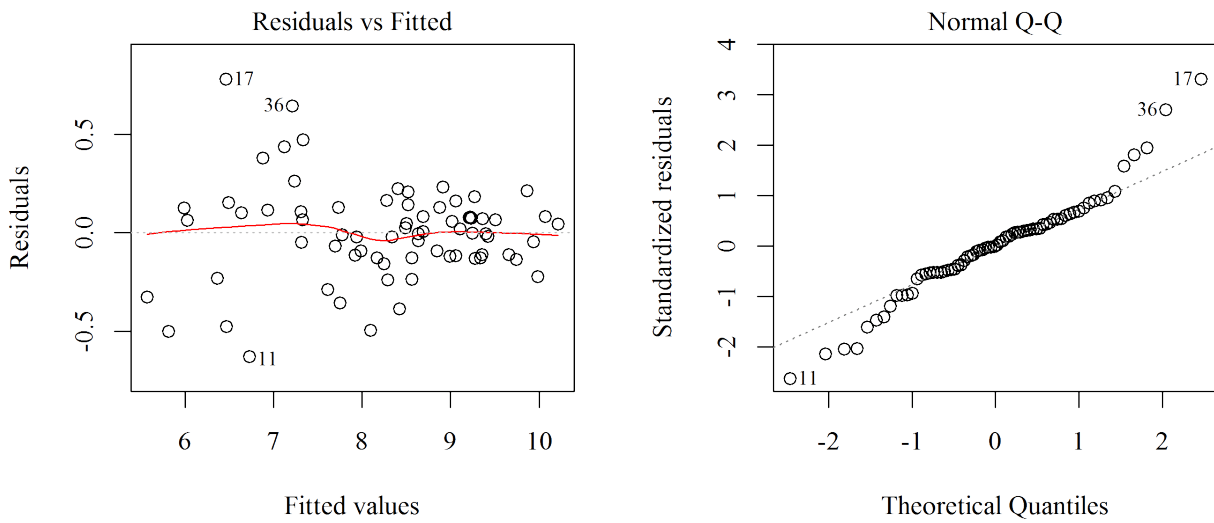

Figure a: Model m4

Figure b: Model m5