

# DATA LEGACY

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## Introduction

In the spirit of expanding the definition of academic success (Goring et al., 2014) and fostering open collegiate science (Hampton et al., 2015), this chapter discusses the products of this PhD project outwith the immediate results-based thesis chapters. It is my hope that the data and research infrastructure generated during this PhD will have a legacy beyond the uses I have found for it thus far, providing value to myself as I progress through my academic career, and to other researchers. Specifically, this chapter discusses the extended value of the data collected during the PhD, the steps taken to ensure that data are visible to and usable by other researchers, existing research outputs by colleagues utilising the data, and a non-exhaustive list of future projects which could use the data in novel and impactful ways.

There are two principal non-chapter outputs of this PhD project. Firstly the network of permanent plots and accompanying census data in Bicuar National Park, southwest Angola, and secondly the terrestrial LiDAR data collected in 22 1 ha plots, including all 15 in Bicuar National Park and a further seven in Kilwa District, southern Tanzania.

## Permanent plots in Bicuar National Park

The 15 1 ha permanent plots in Bicuar National Park were set up in collaboration with Dr. Francisco Maiato Gonçalves from the Herbarium of Lubango, Huíla province, Angola, with the help of a National Geographic Society grant (Grant No. EC-51464R-18). These plots provide not only a valuable dataset of woody stem measurements but also an infrastructure for further ecological research and an opportunity for continued scientific collaboration between the University of Edinburgh and the Herbarium of Lubango.

The Herbarium of Lubango is located ~300 km from Bicuar National Park. During their installation and in the year after, the plots were used by the Instituto de Ciências da Educação Huila (ISCED), which is partnered with the Herbarium of Lubango, to teach Ecology Masters students about woody biomass estimation techniques and plant taxonomy. As teaching resources at public institutions in Angola can be scarce, our partnership with ISCED provides a clear capacity building benefit that will hopefully strengthen academic interest in woodland monitoring programmes at the institution.

A number of voucher specimens from tagged trees in the plots are held in the Herbarium of Lubango, with duplicates of most currently held in the Royal Botanic Gardens at Kew, London, UK. We hope to conduct more botanical collections during future censuses to update the checklist of plant species found in Bicuar National Park, with the hope of raising the profile of this valuable woodland refuge at the far western extent of the miombo ecoregion, and improving its protection and development as a natural resource by the Angolan government. To this end, in 2019, in addition to setting up the 1 ha permanent plots, we conducted 20 one-off 20x50 m samples of previously abandoned agricultural land at the edge of the park boundaries, to improve our coverage of land-use types in the Park and to better understand the biodiversity recovery of regenerating agricultural landscapes.

Steps have been taken to ensure the longevity of the permanent plots. The value of a plot focussed monitoring programme generally increases over time as more data is accrued and temporal trends can be identified, so efforts must be made to ensure that regular censuses and maintenance are conducted. In 2020 all plot corners were marked permanently with concrete posts (Figure 1), and have been located with highly accurate differential-GPS, to an accuracy of  $\leq 3$  cm. Knowing the plot boundaries to a high degree of accuracy will increase their value as plots to be matched with highly precise satellite data products that are currently emerging (Exbrayat et al., 2019; George-Chacon et al., 2019; Wagner et al., 2018).

Data from the first census of the plots are held in the SEOSAW database (SEOSAW, 2020). The SEOSAW database holds standardised woody stem measurements from plots spanning southern Africa. The data in SEOSAW are available to all researchers following agreement by the data

holder and all other SEOSAW members. The permanent plots in Bicuar are the most westerly permanent plots in the SEOSAW plot network (Figure 2), occupying a climate space within the region not currently served by other permanent plots (Figure 3). Holding the plot data from Bicuar in SEOSAW also acts as a permanent data backup repository, extending the lifespan of the data.

A second woody stem biomass survey is planned for all plots in 2022/2023, with the aim of improving the quality of data collected and assessing mortality and productivity over time. This re-census will likely happen as part of either the SEOSAW or SECO projects, both operating out of the University of Edinburgh. Data from the second census will be provided to SEOSAW and eventually uploaded along with the first census to ForestPlots.net (Lopez-Gonzalez et al., 2011), increasing visibility of the data further.



Figure 1: An example of the concrete posts installed to a depth of 1 m at the plot corners of all 1 ha plots in Bicuar National Park, to ensure that plot boundaries are not lost and do not drift over repeated censuses.

Data from these plots have already been utilised in three peer-reviewed articles led by colleagues:

- Grace Jopaul Loubota Panzou et al. (2020). ‘Pantropical variability in tree crown allometry’. In: 30.2. Ed. by Andrew Kerkhoff, pp. 459–475. DOI: [10.1111/geb.13231](https://doi.org/10.1111/geb.13231)
- SEOSAW (2020). ‘A network to understand the changing socio-ecology of the southern African woodlands (SEOSAW): Challenges, benefits, and methods’. In: *Plants, People, Planet*. DOI: [10.1002/ppp3.10168](https://doi.org/10.1002/ppp3.10168)
- Esquivel-Muelbert, A. ... (in prep. Nature Communications 2021). Bridging scales in monitoring tree mortality globally.

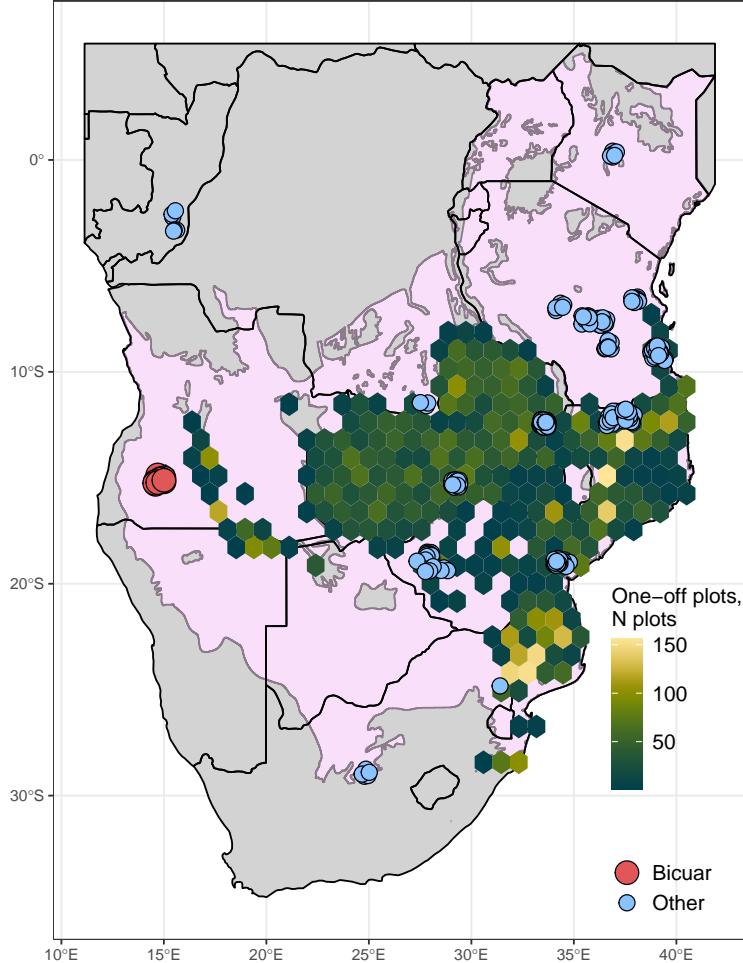


Figure 2: The spatial distribution of plots in the SEOSAW network. Blue circles are permanent plots, where individual stems are tagged and can be matched among censuses. The permanent plots in Bicuar National Park are shown as red points. The hexagon grid shows the density of one-off plots. The pink shading shows the working region of the SEOSAW network, defined primarily from woodland defined by White (1983) and further adapted to bound the north-eastern and southern boundaries.

### Bicuar National Park as a ‘Supersite’

There has been a recent push to establish certain long-term ecological monitoring sites as ‘supersites’. A supersite is defined here as a “highly-instrumented research site where all ecosystem compartments and fluxes are covered” (Mikkelsen et al., 2013). Establishment of supersites has been identified as a goal by a number of international projects which seek to improve global land-atmosphere modelling and monitoring of the effects of climate change on ecosystem structure and function. Notable organisations include the Forest Observation System (FOS, Chave et al. 2019), and the upcoming SECO project at the University of Edinburgh (NERC Large Grant NE/T01279X/1). The impetus behind the supersite model is that it is more cost-effective to prioritise a small number of sites that are representative of a given landscape’s ecology as locations for concentrating multiple expensive measurements, such as LiDAR and atmospheric flux towers. These highly-instrumented sites then form the apex of a hierarchy of sites within the landscape most of which only have limited monitoring measurements. Measurements from the supersites can then be used to ‘scale up’ to the landscape scale with the help of the less-provisioned sites and remotely-sensed data (Anderson, 2018). Concentrating multiple measurements within a few sites allows more ready comparison of these measurements, which when scattered among nearby sites can severely decrease their predictive

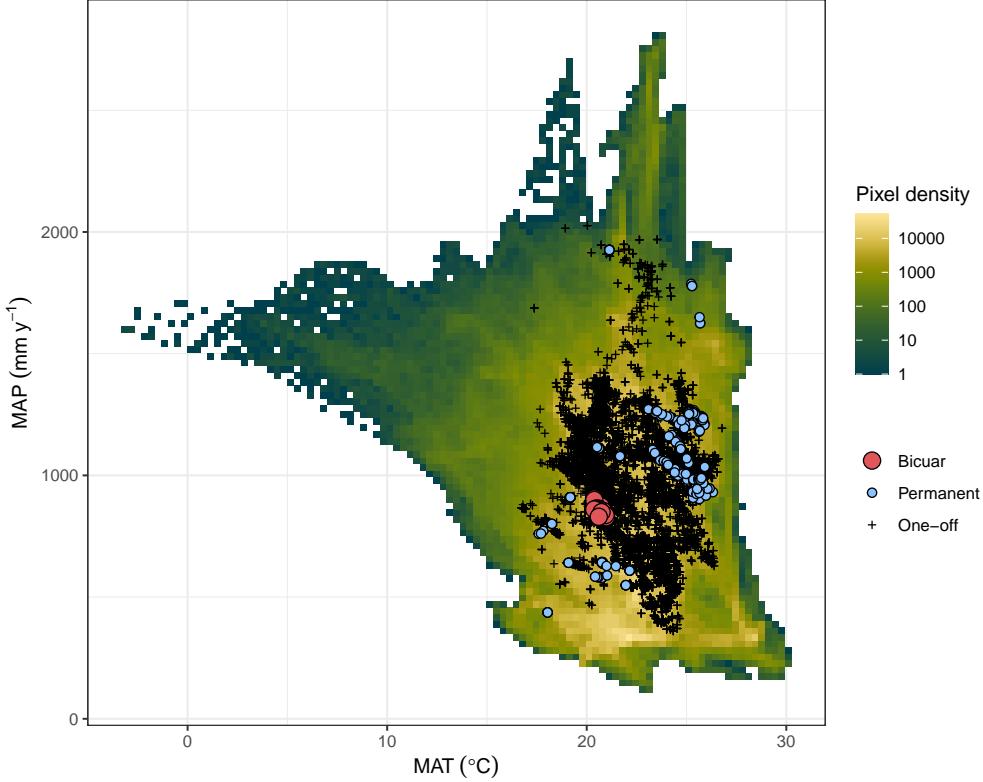


Figure 3: The distribution of SEOSAW plots in climate space, using Mean Annual Temperature (MAT) and Mean Annual Precipitation (MAP) from the WorldClim database (Fick & Hijmans, 2017). Blue circles are permanent plots, where individual stems can be matched among censuses. The permanent plots in Bicuar National Park are shown as red points. Black crosses show one-off plots. The background is shaded according to the density of pixels in the SEOSAW working region, described in Figure 2.

power due to individual site conditions (Mikkelsen et al., 2013).

Some of the common requirements for supersites outlined by various projects have already been fulfilled for the plots in Bicuar National Park. Since 2015, SASSCAL (Southern African Science Service Centre for Climate Change and Adaptive Land Management) has maintained a weather station at Bicuar National Park, providing freely available hourly data on air temperature, solar irradiance, wind speed and direction, soil moisture, precipitation and air pressure (SASSCAL, 2020). The weather station is located within 20 km of all the permanent plots. A critical requirement for a supersite in many projects is that it has a combination of either terrestrial and/or airborne LiDAR measurements. LiDAR provides invaluable information on forest structure that is precisely geo-referenced, helping to bridge the scale gap between ground measurements and satellite measurements. The 15 plots in Bicuar National Park already have a comprehensive terrestrial LiDAR dataset, with precise geo-referencing, collected in 2019. The possibility of repeat LiDAR measurements in combination with an airborne LiDAR campaign would make Bicuar National Park an extremely valuable resource. Additionally, the GEDI L2B satellite LiDAR product has good coverage over Bicuar National Park, with the potential to compare these measurements with the terrestrial LiDAR in the plots (Figure 4). To our knowledge there are no other plot-based terrestrial LiDAR datasets of dry tropical woodlands in southern Africa. Our hope is that Bicuar National Park can be registered as a supersite with one or more research organisation and become a destination for researchers, strengthening the representation of Angolan science, and advertising Bicuar National Park and the Herbarium of Lubango as a destination for researchers, building capacity, research potential and conservation awareness in the region.

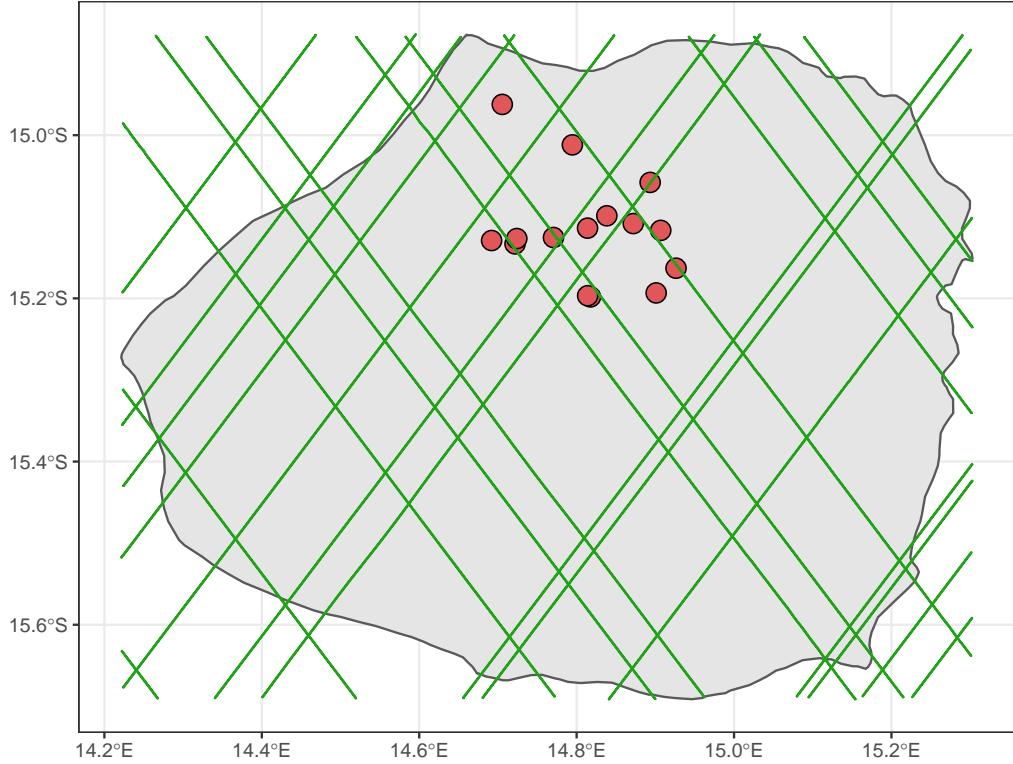


Figure 4: 50 m wide flight-paths of the GEDI L2B satellite LiDAR product (red lines), with the extent of Bicuar National Park (grey polygon), and the locations of the 15 1 ha permanent plots (blue points). Note that in reality each 25 m track consists of a series of 25 m radius circles which contain LiDAR data.

## Terrestrial LiDAR

In addition to the value of terrestrial LiDAR data to qualify as a supersite, as described above, the terrestrial LiDAR data collected as part of this thesis has other uses and values. The LiDAR data has been archived on the University of Edinburgh DataShare, with a permanent DOI ([DOI ID](#)), along with details of the largely free and open source reproducible workflow for processing the data, which is also seen in Chapter 5 of this thesis. When Chapter 5 is eventually published as a peer-reviewed article, the data repository will be advertised in the article. It is my hope that other researchers will use the data for their own research, extending its lifespan to that which befits the effort expended to collect it. An alternative method to increase visibility of the dataset and encourage its use by others could be to publish an article in a journal like “*Data in Brief*”, which specialises in short reports on open-access datasets.

The LiDAR data was collected with multiple uses in mind. The sampling density is sufficient to reliably estimate the canopy height profile of an entire plot, to segment individual trees from the point cloud and to distinguish internal tree canopy architecture. A key application of terrestrial LiDAR is in linking to air- and space-borne LiDAR, and other remotely sensed data products to bridge the scale gap between plot and landscape studies (Xiao et al., 2019). Recent studies have used a combination of terrestrial LiDAR and other remotely-sensed data products to scale up models of functional traits from individual leaves to landscapes (Martínez et al., 2016), calibrate landscape models of biomass distribution (Réjou-Méchain et al., 2019), and infer 3D forest structure with satellite data products (Fischer et al., 2020). Our hope is that the LiDAR data may be used by other researchers in a similar manner to answer questions pertinent to southern African woodlands. The following sections contain justifications for future studies I wish to undertake personally using the data collected during this project.

## Tree taper modelling from Terrestrial LiDAR

The most common way of assessing aboveground woody biomass of trees is through allometric models which estimate biomass from a combination of stem diameter, tree height and wood density (Chave et al., 2014). These allometric models often assume that stem diameter is measured at a height of 1.3 m, a convention that is widely followed across forestry and ecology (Brokaw & Thompson, 2000). Peculiarities in stem shape occasionally require the measurement of stem diameter at a different height however, to avoid abnormalities such as burls, fluting, or branch nodes that would otherwise provide an unrepresentative estimate of stem diameter if measured at the conventional height (Kershaw et al., 2017). On average, stem diameter tapers towards the top of a tree (Kozak et al., 1969), meaning that without proper correction, biomass estimates generated from these diameter measurements at unconventional heights will over- or under-estimate biomass.

Many models of stem taper have been developed, being used by foresters for over a century to estimate harvestable timber volumes, and are still the subject of active development (MacFarlane & Weiskittel, 2016; Luoma et al., 2019). As well as estimating harvestable volume, stem taper models can be used to correct for variation in stem diameter measurement height, to ensure consistent estimates of woody biomass or harvestable volume. Previously these models have been parameterised through multiple measures of stem diameter at different heights with a tape measure, but this is time-consuming and suffers from the same imprecision and human error as any other diameter tape measurement (Saarinen et al., 2019).

Plot-based estimation of woody biomass across the globe currently relies on measuring stem diameter (SEOSAW, 2020; Chave et al., 2005; Schepaschenko et al., 2019). Being able to accurately reconcile stem diameters measured at different heights is therefore paramount to improving our models of above-ground woody biomass.

Rapid progress has been made in methods to model woody stem diameter from terrestrial LiDAR point clouds (Bogdanovich et al., 2021; Hopkinson et al., 2004; Srinivasan et al., 2015; Ravaglia et al., 2019). These methods estimate a cylinder of the stem from a slice of points, with recent advancements allowing interpolation of the cylinder even when the coverage of laser returns on the stem surface is incomplete. Others have extended the method to generate estimates of stem taper (Henning & Radtke, 2006; Thies et al., 2004), but to our knowledge this has not been done for any tree species growing the dry tropics. The terrestrial LiDAR data collected in Angola and Tanzania provide the opportunity to conduct this first study of stem taper from LiDAR measurements in the dry tropics. The species, locations, and stem diameters of all stems  $>5$  cm diameter is known within these plots, meaning that these data can be matched with stems observable in the LiDAR point cloud. As a proof of concept, I have developed a prototype stem segmentation using `treeseg` (Burt et al., 2018), and a cylinder interpolation method based on Umbach & Jones (2003), which estimates stem diameter at multiple heights along the tree stem (Figure 5).

## Biomass of large trees: testing scaling theory for estimating biomass

Large diameter trees hold a disproportionately large amount of woody biomass in most wooded ecosystems (Bastin et al., 2015; Lutz et al., 2018). To accurately describe the woody biomass stocks of a particular system, more effort should therefore be allocated to accurately estimating the biomass of the largest trees. Woody biomass is most commonly estimated through allometric equations which rely on measures of stem diameter, tree height and woody density. At the root of these allometric equations are a limited number of destructive biomass harvests, which define the relationship between tree physiognomic measurements and the biomass of the harvested tree (Chave et al., 2005). Biomass harvesting is time consuming, expensive, and understandably not a popular activity among ecologists due to its destructive nature (Roxburgh et al., 2015). Furthermore, allometric equations are often least well defined for the largest trees, as large trees are scarcer than small trees (Lutz et al., 2018; Lindenmayer et al., 2012), and even less likely to be cut down during destructive harvests due to the cultural and aesthetic value they hold as living organisms (Blicharska & Mikusiński, 2014).

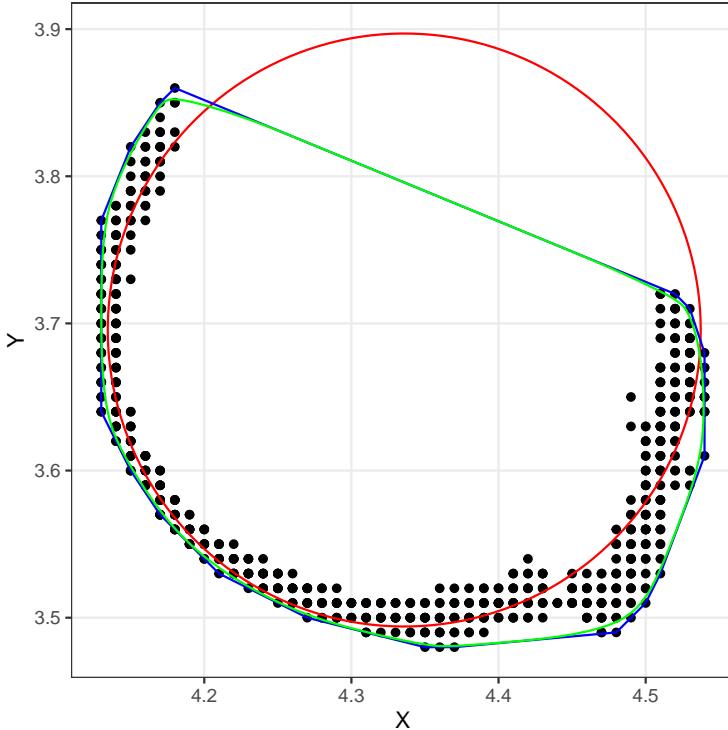


Figure 5: Example output of the prototype stem cylinder interpolation method used to estimate stem diameter from an incomplete point cloud. Voxelised points at  $2 \text{ cm}^3$  are shown as black points. Interpolation methods are shown as coloured polygons. The interpolated stem cylinder method based on Umbach & Jones (2003) is shown in red. A convex hull of all points is shown in blue. A kernel smoothing method using Gaussian kernel regression is shown in green.

Specifically the parameterisation of the exponent term of traditional diameter-biomass allometry power-models is often poor for large trees, and there is a heteroscedastic relationship between diameter and biomass at higher stem diameters (Figure 6) (Chave et al., 2004; Chave et al., 2014). Recently, the suitability of power-models for diameter-biomass allometries has even been drawn into question, though an alternative that works globally has not yet been found (Picard et al., 2015). Weighting procedures so that large rare trees with higher intrinsic variability in biomass do not overly influence model coefficients have been used successfully previously (Chave et al., 2014; McNicol et al., 2015), but this does not solve the root problem that the biomass of newly encountered large trees will likely be poorly estimated.

As the age of a tree increases, it generates an idiosyncratic physiognomy due to the amassed disturbances and variations in environment it has encountered (Lindenmayer & Laurance, 2016). Large trees often have hollow trunks (fluting) or areas of punky wood (Chambers et al., 2001; Ruxton, 2014), which may lead to a large over-estimation of biomass if not accounted for (Figure 8). The correlation between main stem diameter and the woody biomass held in other tree components such upper canopy branches tends to become weaker in larger trees, meaning that simple stem diameter measurements cannot accurately represent whole tree biomass (Goodman et al., 2014; Saglam et al., 2020). In disturbance-prone tropical savannas, it may be expected that the issue of idiosyncratic physiognomy is even greater, as trees repeatedly re-grow following seasonal fire and damage by large herbivores, further reducing the accuracy of biomass estimations (Figure 7). For the reasons outlined above, it is therefore of great importance to develop an optimal method for estimating biomass of the largest trees. But how do we reconcile the disproportionate contribution of large trees to plot-based estimates of biomass with the scarcity of destructive large tree measurements?

Terrestrial LiDAR provides an opportunity to accurately estimate the woody volume of very large trees. Recent advances have provided a number of methods for segmenting individual trees from a

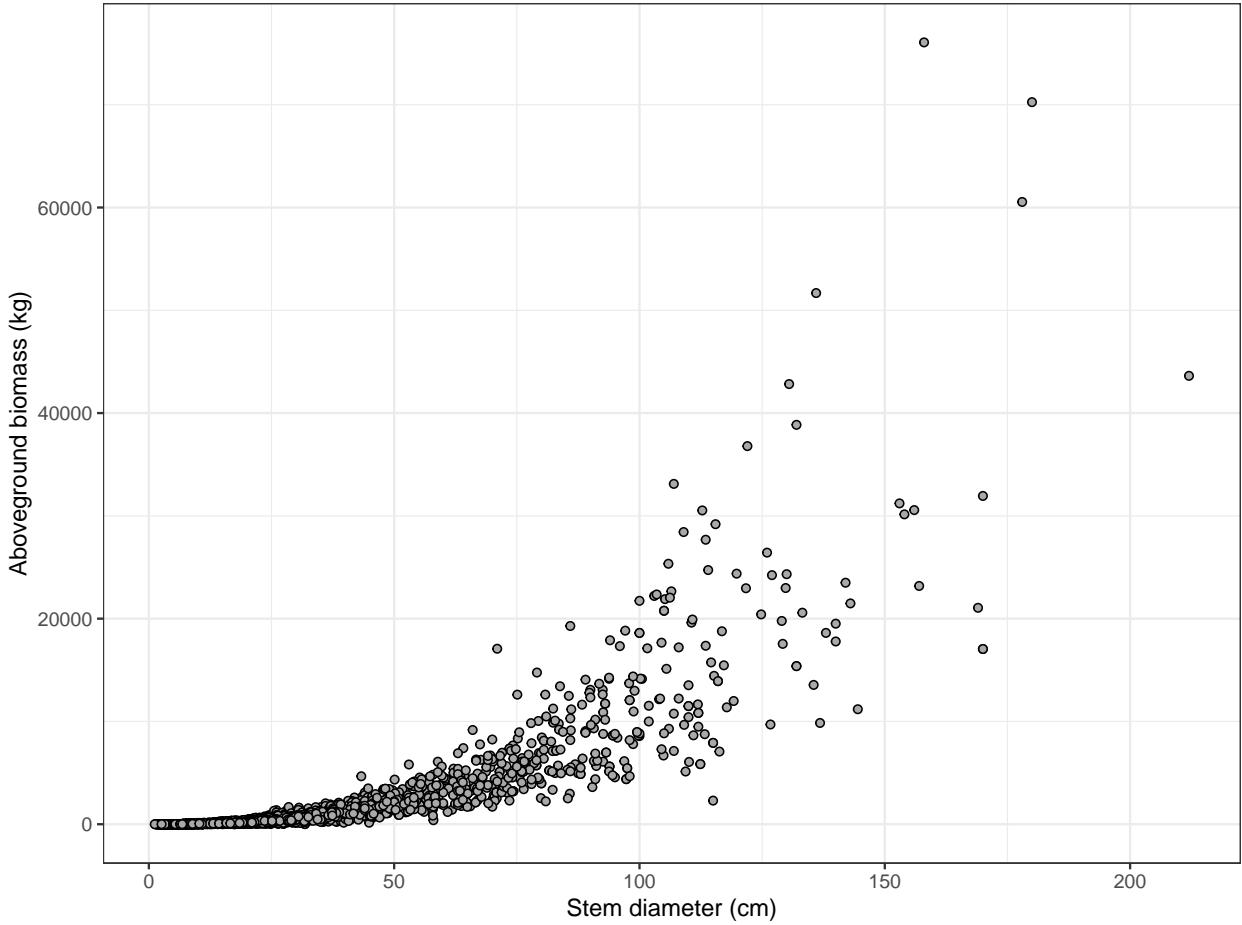


Figure 6: The relationship between tree stem diameter and aboveground biomass calculated from destructive harvest from all 872 records held in the GlobAllomeTree database (Henry et al., 2013) and all 4004 records reported in Chave et al. (2014). The heteroscedasticity of the relationship between stem diameter and aboveground biomass can be seen, with increased variance in biomass at higher stem diameters.

point cloud (Burt et al., 2018; Koma et al., 2018), and for generating 3D surface models from point clouds (Calders et al., 2014; Malhi et al., 2018) to build voluminous models of individual trees. The plots covered by the terrestrial LiDAR dataset collected during this thesis contain 86 trees  $>50$  cm stem diameter with 360° point cloud coverage, providing decent replication if each tree is successfully segmented.

While terrestrial LiDAR may address inaccurate biomass estimates caused by idiosyncratic physiognomy present on the exterior surface of large trees, and has been used successfully for this purpose in other studies (Takoudjou et al., 2017), it cannot address the internal variation caused by fluting and hollowing that is pervasive in large trees. It is also affected by the thick bark present in many fire-adapted savanna trees, which can lead to an over-estimation of woody biomass (Kozak & Smith, 1993; Hoffmann et al., 2012; Solbrig et al., 1996). Sonic tomography has been developed as a method to measure the decay of wood within tree trunks (Gilbert et al., 2016), and is currently used routinely to detect structural weaknesses in large trees in urban and parkland areas (Karlinasari et al., 2018). The PiCUS sonic tomograph (Argus Electronics GmbH, Rostock, Germany) is suitable for detecting internal abnormalities in large woody stems, and has been used previously to estimate biomass in forest trees (Marra et al., 2018).

I aim to test a novel method for estimating the biomass of the largest trees in the 22 plots already covered by the terrestrial LiDAR dataset, using a combination of terrestrial LiDAR and sonic tomography, to map the exterior and interior of the tree, respectively. LiDAR and tomography meas-

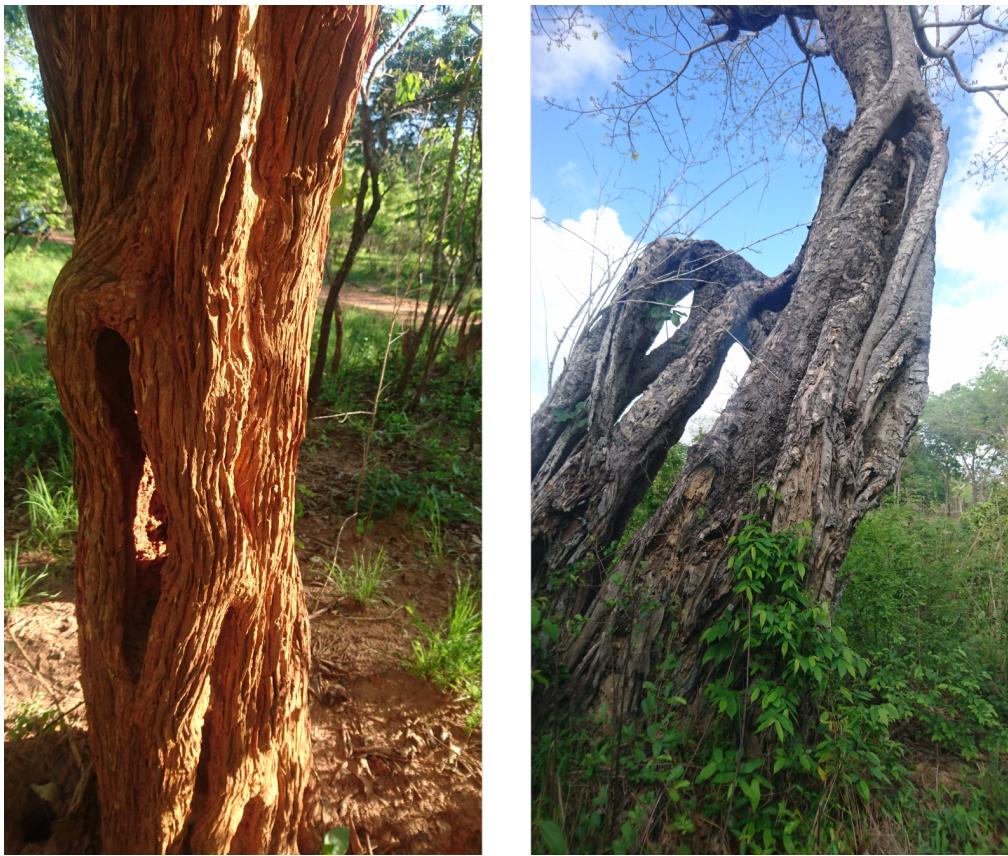


Figure 7: Two large old trees in Kilwa District, southeast Tanzania, with particularly idiosyncratic trunks. Using conventional stem diameter allometries will likely produce an inaccurate estimate of above-ground biomass. Photos by Ellie Wood.

urements will be combined with conventional measurements of tree stem diameter, tree height, and wood density, to build a multi-input allometric model of large trees with the hope of further reducing the large uncertainty in the woody biomass stocks of southern African woodlands. Additionally, the new biomass estimations will be compared to biomass estimates generated from existing allometric equations for dry tropical trees, e.g. Chave et al. (2014) and Ryan et al. (2011), to assess whether these allometries produce an over- or under-estimation of biomass. Specifically, I propose to use the PiCUS 3 sonic tomograph with the protocol outlined in Gilbert et al. (2016) to measure internal structure, and the pipe-fitting algorithm from Calders et al. (2014) to create 3D branch models of exterior structure. Ideally the fieldwork for this project could be carried out alongside a repeat census of the permanent plots, which in Bicuar National Park will happen in either 2022 or 2023, taking advantage of the existing plot monitoring infrastructure and existing LiDAR data.

### **Effects of canopy structure on understorey light environment and grass biomass**

The competitive balance between grass and trees defines mesic savanna ecosystems (Frost, 1996). Where rainfall does not preclude a closed tree canopy (Sankaran et al., 2005), disturbance by fire can prevent canopy closure via a positive feedback loop whereby an open canopy allows grass growth, providing fuel for more frequent and intense fires, causing tree mortality, particularly among juveniles, preventing canopy closure, and so on (Staver et al., 2011). This positive feedback drives the phenomenon of ‘alternative stable states’, where nearby and environmentally similar patches can maintain different vegetation based on previous disturbance history. This commonly produces a mosaic of open savanna patches and closed canopy forest-like patches.

Much previous research has tried to identify the factors which determine the spatial patterning of closed and open canopy patches in mesic savannas, and particularly the factors determining the



Figure 8: A severely fluted *Brachystegia tamarindoides* stem found in Bicuar National Park, Angola. Due to the decomposition of wood in the stem interior, simple stem diameter based biomass allometries will over-estimate the biomass of this stem.

resilience of patches to state transitions (Devine et al., 2017; Case & Staver, 2016; Hirota et al., 2011). Of particular interest has been the transition from open savanna to a closed canopy forest-like state, as evidence suggests that atmospheric carbon fertilisation may be driving woody encroachment and woody thickening across mesic savannas (Stevens et al., 2017). Most previous work has focussed on climatic (Case et al., 2020), edaphic (Colgan et al., 2012) and disturbance factors (Case & Staver, 2016), and how these interact with tree and grass growth to determine their competitive balance, but few have considered biotic factors such as tree demographic structure, canopy architecture and tree species composition (but see Pilon et al. 2020), which may also influence grass growth (Jennings, 1999). The LiDAR data collected during this PhD provides a unique opportunity to investigate the relationship between canopy tree attributes and grass biomass, to draw conclusions about the tree canopy conditions which provide resilience in open and closed canopy states.

Although the data was not included in the thesis due to lack of time for analysis, the terrestrial LiDAR dataset collected in Bicuar National Park was paired with systematic grass biomass harvest samples and grass sward height measurements using a Disc Pasture Meter (DPM), across all 15 plots (Figure 10). Cooper et al. (2017) provides a method for estimating grass volume from terrestrial LiDAR, which could be extended in this study to estimate grass biomass through an allometric

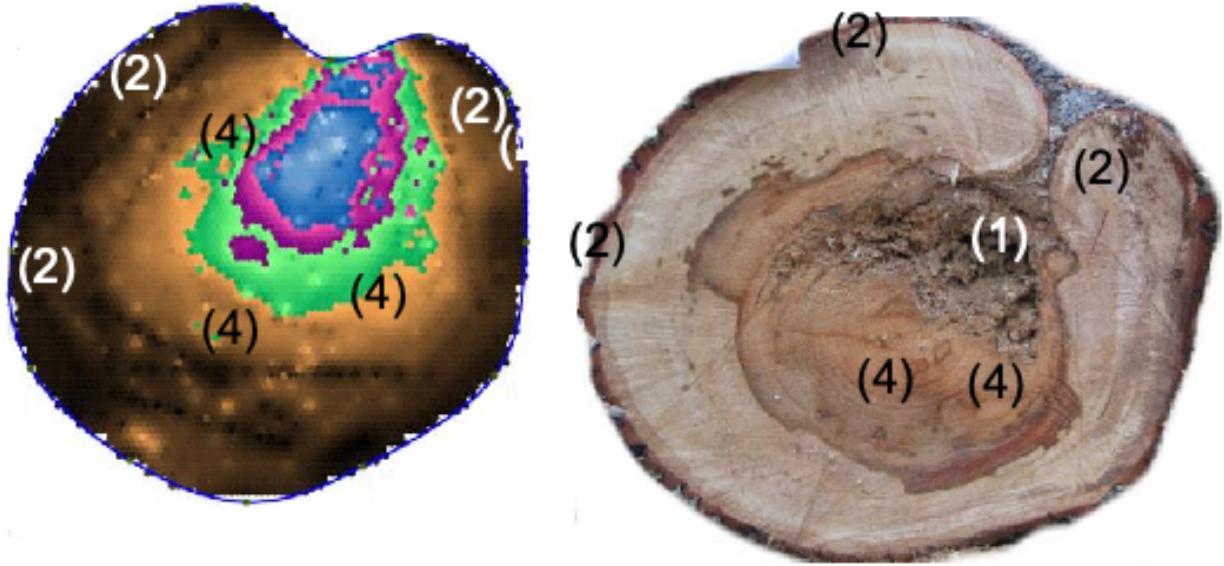


Figure 9: An example of a sonic tomograph image (left) and across section of the same tree (right), annotated to show internal features of the stem: (1) cavity or dead dry wood, (2) sound wood, (4) active decay with dense wood. Taken from Argus Electronic GmbH (2016).

equation linking grass volume to sward height and biomass harvests. The sample locations of the grass measurements are precisely known from differential-GPS and can therefore be matched precisely with the LiDAR measurements, providing data on canopy structure at the fine spatial scale relevant to grass growth.

Using simple linear mixed effects models to explore the relative importance of different tree canopy architectural and structural properties, these data could be used to improve our understanding the drivers of woody encroachment and alternative stable states, which could be applied to earth system models at regional spatial scales to predict how resilient different vegetation types are to environmental change, with consequences for biomass and carbon cycling predictions.

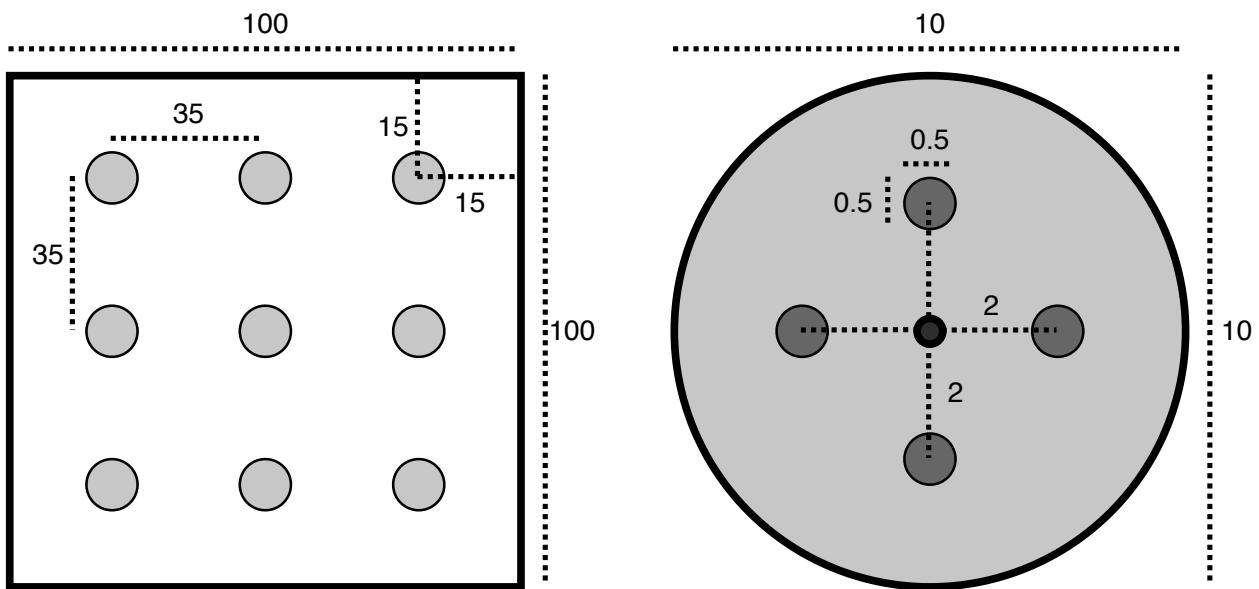


Figure 10: The layout of 10 m diameter subplots within each 1 ha square plot. Distances are marked by dotted lines, in metres. Each subplot is situated inside a 15 m buffer from the plot edge, with 35 m between subplot centres. Subplots are arranged in a 3x3 grid. Disc Pasture Measurements (DPM) and biomass samples are located in cardinal directions 2 m from the centre of the subplot. All distances are in metres. Biomass harvests were conducted at one randomly selected DPM sample point per subplot, resulting in nine biomass harvests and 36 DPM samples per 1 ha plot.

## References

- Anderson, Christopher B. (2018). ‘Biodiversity monitoring, earth observations and the ecology of scale’. In: *Ecology Letters* 21.10. Ed. by Nick Haddad, pp. 1572–1585. DOI: 10.1111/ele.13106.
- Argus Electronic GmbH (2016). *PicUS tree tomography methods at a glance*. Rostock, Germany: Argus Electronic GmbH.
- Bastin, J.-F., N. Barbier, M. Réjou-Méchain, A. Fayolle, S. Gourlet-Fleury, D. Maniatis, T. de Haulleville, F. Baya, H. Beeckman, D. Beina et al. (2015). ‘Seeing Central African forests through their largest trees’. In: *Scientific Reports* 5.1. DOI: 10.1038/srep13156.
- Blicharska, M. & G. Mikusiński (2014). ‘Incorporating Social and Cultural Significance of Large Old Trees in Conservation Policy’. In: *Conservation Biology* 28.6, pp. 1558–1567. DOI: 10.1111/cobi.12341.
- Bogdanovich, Ekaterina, Oscar Perez-Priego, Tarek S. El-Madany, Marcus Guderle, Javier Pacheco-Labrador, Shaun R. Levick, Gerardo Moreno, Arnaud Carrara, M. Pilar Martín & Mirco Migliavacca (2021). ‘Using terrestrial laser scanning for characterizing tree structural parameters and their changes under different management in a Mediterranean open woodland’. In: *Forest Ecology and Management* 486, p. 118945. DOI: 10.1016/j.foreco.2021.118945.
- Brokaw, Nicholas & Jill Thompson (2000). ‘The H for DBH’. In: *Forest Ecology and Management* 129.1-3, pp. 89–91. DOI: 10.1016/s0378-1127(99)00141-3.
- Burt, Andrew, Mathias Disney & Kim Calders (2018). ‘Extracting individual trees from lidar point clouds using treeseg’. In: *Methods in Ecology and Evolution*. Ed. by Sarah Goslee. DOI: 10.1111/2041-210x.13121.
- Calders, Kim, Glenn Newnham, Andrew Burt, Simon Murphy, Pasi Raunonen, Martin Herold, Darius Culvenor, Valerio Avitabile, Mathias Disney, John Armston et al. (2014). ‘Nondestructive estimates of above-ground biomass using terrestrial laser scanning’. In: *Methods in Ecology and Evolution* 6.2. Ed. by Sean McMahon, pp. 198–208. DOI: 10.1111/2041-210x.12301.
- Case, Madelon F., Jesse B. Nippert, Ricardo M. Holdo & A. Carla Staver (2020). ‘Root-niche separation between savanna trees and grasses is greater on sandier soils’. In: *Journal of Ecology* 108.6. Ed. by Imma Oliveras, pp. 2298–2308. DOI: 10.1111/1365-2745.13475.
- Case, Madelon F. & A. Carla Staver (2016). ‘Fire prevents woody encroachment only at higher-than-historical frequencies in a South African savanna’. In: 54.3. Ed. by Jeremy James, pp. 955–962. DOI: 10.1111/1365-2664.12805.
- Chambers, Jeffrey Q., Joaquim dos Santos, Ralph J. Ribeiro & Niro Higuchi (2001). ‘Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest’. In: *Forest Ecology and Management* 152.1-3, pp. 73–84. DOI: 10.1016/s0378-1127(00)00591-0.
- Chave, J., C. Andalo, S. Brown, M. A. Cairns, J. Q. Chambers, D. Eamus, H. Fölster, F. Fromard, N. Higuchi, T. Kira et al. (2005). ‘Tree allometry and improved estimation of carbon stocks and balance in tropical forests’. In: *Oecologia* 145.1, pp. 87–99. DOI: 10.1007/s00442-005-0100-x.

- Chave, J., M. Réjou-Méchain, A. Bürquez, E. Chidumayo, M. S. Colgan, W. B. C. Delitti, A. Duque, T. Eid, P. M. Fearnside, R. C. Goodman et al. (2014). 'Improved allometric models to estimate the aboveground biomass of tropical trees'. In: *Global Change Biology* 20, pp. 3177–3190. doi: 10.1111/gcb.12629.
- Chave, Jerome, Richard Condit, Salomon Aguilar, Andres Hernandez, Suzanne Lao & Rolando Perez (2004). 'Error propagation and scaling for tropical forest biomass estimates'. In: *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 359.1443. Ed. by Y. Malhi & O. L. Phillips, pp. 409–420. doi: 10.1098/rstb.2003.1425.
- Chave, Jérôme, Stuart J. Davies, Oliver L. Phillips, Simon L. Lewis, Plinio Sist, Dmitry Schepaschenko, John Armston, Tim R. Baker, David Coomes, Mathias Disney et al. (2019). 'Ground Data are Essential for Biomass Remote Sensing Missions'. In: *Surveys in Geophysics* 40.4, pp. 863–880. doi: 10.1007/s10712-019-09528-w.
- Colgan, M. S., G. P. Asner, S. R. Levick, R. E. Martin & O. A. Chadwick (2012). 'Topo-edaphic controls over woody plant biomass in South African savannas'. In: 9.5, pp. 1809–1821. doi: 10.5194/bg-9-1809-2012.
- Cooper, Sam, David Roy, Crystal Schaaf & Ian Paynter (2017). 'Examination of the Potential of Terrestrial Laser Scanning and Structure-from-Motion Photogrammetry for Rapid Nondestructive Field Measurement of Grass Biomass'. In: 9.6, p. 531. doi: 10.3390/rs9060531.
- Devine, Aisling P., Robbie A. McDonald, Tristan Quaife & Ilya M. D. Maclean (2017). 'Determinants of woody encroachment and cover in African savannas'. In: 183.4, pp. 939–951. doi: 10.1007/s00442-017-3807-6.
- Exbrayat, Jean-François, A. Anthony Bloom, Nuno Carvalhais, Rico Fischer, Andreas Huth, Natasha MacBean & Mathew Williams (2019). 'Understanding the Land Carbon Cycle with Space Data: Current Status and Prospects'. In: *Surveys in Geophysics* 40.4, pp. 735–755. doi: 10.1007/s10712-019-09506-2.
- Fick, S. E. & R. J. Hijmans (2017). 'WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas'. In: *International Journal of Climatology* 37.12, pp. 4302–4315. doi: 10.1002/joc.5086.
- Fischer, F. J., N. Labrière, G. Vincent, B. Hérault, A. Alonso, H Memiaghe, P. Bissengou, D. Kenfack, S. Saatchi & J. Chave (2020). 'A simulation method to infer tree allometry and forest structure from airborne laser scanning and forest inventories'. In: *Remote Sensing of Environment* 251, p. 112056. doi: 10.1016/j.rse.2020.112056.
- Frost, P. (1996). 'The ecology of miombo woodlands'. In: *The miombo in transition: woodlands and welfare in Africa*. Ed. by B.M. Campbell. Bogor, Indonesia: Center for International Forestry Research, pp. 11–55.
- George-Chacon, Stephanie P., Juan Manuel Dupuy, Alicia Peduzzi & J. Luis Hernandez-Stefanoni (2019). 'Combining high resolution satellite imagery and lidar data to model woody species diversity of tropical dry forests'. In: *Ecological Indicators* 101, pp. 975–984. doi: 10.1016/j.ecolind.2019.02.015.
- Gilbert, Gregory S., Javier O. Ballesteros, Cesar A. Barrios-Rodriguez, Ernesto F. Bonadies, Marjorie L. Cedeño-Sánchez, Nohely J. Fossatti-Caballero, Mariam M. Trejos-Rodríguez, José Moises Pérez-Suñiga, Katharine S. Holub-Young, Laura A. W. Henn et al. (2016). 'Use of Sonic Tomography to Detect and Quantify Wood Decay in Living Trees'. In: *Applications in Plant Sciences* 4.12, p. 1600060. doi: 10.3732/apps.1600060.
- Goodman, Rosa C., Oliver L. Phillips & Timothy R. Baker (2014). 'The importance of crown dimensions to improve tropical tree biomass estimates'. In: *Ecological Applications* 24.4, pp. 680–698. doi: 10.1890/13-0070.1.
- Goring, Simon J., Kathleen C Weathers, Walter K Dodds, Patricia A Soranno, Lynn C Sweet, Kendra S Cheruvellil, John S Kominoski, Janine Rüegg, Alexandra M Thorn & Ryan M Utz (2014). 'Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success'. In: *Frontiers in Ecology and the Environment* 12.1, pp. 39–47. doi: 10.1890/120370.
- Hampton, Stephanie E., Sean S. Anderson, Sarah C. Bagby, Corinna Gries, Xueying Han, Edmund M. Hart, Matthew B. Jones, W. Christopher Lenhardt, Andrew MacDonald, William K. Michener et al. (2015). 'The Tao of open science for ecology'. In: *Ecosphere* 6.7, art120. doi: 10.1890/es14-00402.1.
- Henning, J. G. & P. J. Radtke (2006). 'Detailed stem measurements of standing trees from ground-based scanning LiDAR'. In: *Forest Science* 52.1, pp. 67–80. doi: 10.1093/forestscience/52.1.67.
- Henry, M, A Bombelli, C Trotta, A Alessandrini, L Birigazzi, G Sola, G Vieilledent, P Santenoise, F Longuetaud, R Valentini et al. (2013). 'GlobAllomeTree: international platform for tree allometric equations to support volume, biomass and carbon assessment'. In: *iForest - Biogeosciences and Forestry* 6.6, pp. 326–330. doi: 10.3832/ifor0901-006.
- Hirota, M., M. Holmgren, E. H. Van Nes & M. Scheffer (2011). 'Global resilience of tropical forest and savanna to critical transitions'. In: *Science* 334, pp. 232–235. doi: 10.1126/science.1210657.
- Hoffmann, William A., Erika L. Geiger, Sybil G. Gotsch, Davi R. Rossatto, Lucas C. R. Silva, On Lee Lau, M. Haridasan & Augusto C. Franco (2012). 'Ecological thresholds at the savanna-forest boundary: how plant traits, resources and fire govern the distribution of tropical biomes'. In: *Ecology Letters* 15.7. Ed. by Francisco Lloret, pp. 759–768. doi: 10.1111/j.1461-0248.2012.01789.x.
- Hopkinson, Chris, Laura Chasmer, Colin Young-Pow & Paul Treitz (2004). 'Assessing forest metrics with a ground-based scanning lidar'. In: *Canadian Journal of Forest Research* 34.3, pp. 573–583. doi: 10.1139/x03-225.
- Jennings, S. (1999). 'Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures'. In: 72.1, pp. 59–74. doi: 10.1093/forestry/72.1.59.
- KarlinaSari, L, A T Lestari, M Y S Nababan, I Z Siregar & D Nandika (2018). 'Assessment of urban tree condition using sonic tomography technology'. In: *IOP Conference Series: Earth and Environmental Science* 203, p. 012030. doi: 10.1088/1755-1315/203/1/012030.
- Kershaw, J. A., M. J. Ducey, T. W. Beers & B. Husch (2017). *Forest Mensuration*. Chichester, UK: John Wiley & Sons.

- Koma, Zs., M. Rutzinger & M. Bremer (2018). ‘Automated Segmentation of Leaves From Deciduous Trees in Terrestrial Laser Scanning Point Clouds’. In: *IEEE Geoscience and Remote Sensing Letters* 15.9, pp. 1456–1460. doi: 10.1109/lgrs.2018.2841429.
- Kozak, A., D. D. Munro & J. H. G. Smith (1969). ‘Taper Functions and their Application in Forest Inventory’. In: *The Forestry Chronicle* 45.4, pp. 278–283. doi: 10.5558/tfc45278-4.
- Kozak, A. & J. H. G. Smith (1993). ‘Standards for evaluating taper estimating systems’. In: *The Forestry Chronicle* 69.4, pp. 438–444. doi: 10.5558/tfc69438-4.
- Lindenmayer, D. B., W. F. Laurance & J. F. Franklin (2012). ‘Global Decline in Large Old Trees’. In: *Science* 338.6112, pp. 1305–1306. doi: 10.1126/science.1231070.
- Lindenmayer, David B. & William F. Laurance (2016). ‘The ecology, distribution, conservation and management of large old trees’. In: *Biological Reviews* 92.3, pp. 1434–1458. doi: 10.1111/brv.12290.
- Lopez-Gonzalez, Gabriela, Simon L. Lewis, Mark Burkitt & Oliver L. Phillips (2011). ‘ForestPlots.net: a web application and research tool to manage and analyse tropical forest plot data’. In: *Journal of Vegetation Science* 22.4, pp. 610–613. doi: 10.1111/j.1654-1103.2011.01312.x.
- Luoma, Ville, Ninni Saarinen, Ville Kankare, Topi Tanhuanpää, Harri Kaartinen, Antero Kukko, Markus Holopainen, Juha Hyypä & Mikko Vastaranta (2019). ‘Examining Changes in Stem Taper and Volume Growth with Two-Date 3D Point Clouds’. In: *Forests* 10.5, p. 382. doi: 10.3390/f10050382.
- Lutz, James A., Tucker J. Furniss, Daniel J. Johnson, Stuart J. Davies, David Allen, Alfonso Alonso, Kristina J. Anderson-Teixeira, Ana Andrade, Jennifer Baltzer, Kendall M. L. Becker et al. (2018). ‘Global importance of large-diameter trees’. In: *Global Ecology and Biogeography* 27.7, pp. 849–864. doi: 10.1111/geb.12747.
- MacFarlane, David W. & Aaron R. Weiskittel (2016). ‘A new method for capturing stem taper variation for trees of diverse morphological types’. In: *Canadian Journal of Forest Research* 46.6, pp. 804–815. doi: 10.1139/cjfr-2016-0018.
- Malhi, Yadvinder, Tobias Jackson, Lisa Patrick Bentley, Alvaro Lau, Alexander Shenkin, Martin Herold, Kim Calders, Harm Bartholomeus & Mathias I. Disney (2018). ‘New perspectives on the ecology of tree structure and tree communities through terrestrial laser scanning’. In: *Interface Focus* 8.2, p. 20170052. doi: 10.1098/rsfs.2017.0052.
- Marra, Robert E, Nicholas J Brazeé & Shawn Fraver (2018). ‘Estimating carbon loss due to internal decay in living trees using tomography: implications for forest carbon budgets’. In: *Environmental Research Letters* 13.10, p. 105004. doi: 10.1088/1748-9326/aae2bf.
- Martínez, Oscar J. Abelleira, Alexander K. Fremier, Sven Günter, Zayra Ramos Bendaña, Lee Vierling, Sara M. Galbraith, Nilsa A. Bosque-Pérez & Jenny C. Ordoñez (2016). ‘Scaling up functional traits for ecosystem services with remote sensing: concepts and methods’. In: *Ecology and Evolution* 6.13, pp. 4359–4371. doi: 10.1002/ece3.2201.
- McNicol, Iain M., Nicholas J. Berry, Thilde Bech Bruun, Kristell Hergoualc'h, Ole Mertz, Andreas de Neergaard & Casey M. Ryan (2015). ‘Development of allometric models for above and belowground biomass in swidden cultivation fallows of Northern Laos’. In: *Forest Ecology and Management* 357, pp. 104–116. doi: 10.1016/j.foreco.2015.07.029.
- Mikkelsen, Teis Nørgaard, Nicholas Clarke, Alina Danielewska & Richard Fischer (2013). ‘Towards Supersites in Forest Ecosystem Monitoring and Research’. In: *Developments in Environmental Science*. Elsevier, pp. 475–496. doi: 10.1016/b978-0-08-098349-3.00022-0.
- Panzou, Grace Jopaul Loubota, Adeline Fayolle, Tommaso Jucker, Oliver L. Phillips, Stephanie Bohlman, Lindsay F. Banin, Simon L. Lewis, Kofi Affum-Baffoe, Luciana F. Alves, Cécile Antin et al. (2020). ‘Pantropical variability in tree crown allometry’. In: 30.2. Ed. by Andrew Kerkhoff, pp. 459–475. doi: 10.1111/geb.13231.
- Picard, Nicolas, Ervan Rutishauser, Pierre Ploton, Alfred Ngomanda & Matieu Henry (2015). ‘Should tree biomass allometry be restricted to power models?’ In: *Forest Ecology and Management* 353, pp. 156–163. doi: 10.1016/j.foreco.2015.05.035.
- Pilon, Natasha A. L., Giselda Durigan, Jess Rickenback, R. Toby Pennington, Kyle G. Dexter, William A. Hoffmann, Rodolfo C. R. Abreu & Caroline E. R. Lehmann (2020). ‘Shade alters savanna grass layer structure and function along a gradient of canopy cover’. In: 32.1. Ed. by Francisco Pugnaire. doi: 10.1111/jvs.12959.
- Ravaglia, Fournier, Bac, Véga, Côté, Piboule & Rémillard (2019). ‘Comparison of Three Algorithms to Estimate Tree Stem Diameter from Terrestrial Laser Scanner Data’. In: *Forests* 10.7, p. 599. doi: 10.3390/f10070599.
- Réjou-Méchain, Maxime, Nicolas Barbier, Pierre Couteron, Pierre Ploton, Grégoire Vincent, Martin Herold, Stéphane Mermoz, Sasan Saatchi, Jérôme Chave, Florian de Boissieu et al. (2019). ‘Upscaling Forest Biomass from Field to Satellite Measurements: Sources of Errors and Ways to Reduce Them’. In: *Surveys in Geophysics* 40.4, pp. 881–911. doi: 10.1007/s10712-019-09532-0.
- Roxburgh, S. H., K. I. Paul, D. Clifford, J. R. England & R. J. Raison (2015). ‘Guidelines for constructing allometric models for the prediction of woody biomass: How many individuals to harvest?’ In: *Ecosphere* 6.3, art38. doi: 10.1890/es14-00251.1.
- Ruxton, Graeme D. (2014). ‘Why are so many trees hollow?’ In: *Biology Letters* 10.11, p. 20140555. doi: 10.1098/rsbl.2014.0555.
- Ryan, C. M., M. Williams & J. Grace (2011). ‘Above- and belowground carbon stocks in a miombo woodland landscape of Mozambique’. In: *Biotropica* 43.4, pp. 423–432. doi: 10.1111/j.1744-7429.2010.00713.x.

- Saarinen, Ninni, Ville Kankare, Jiri Pyörälä, Tuomas Yrttimaa, Xinlian Liang, Michael A. Wulder, Markus Holopainen, Juha Hyppä & Mikko Vastaranta (2019). ‘Assessing the Effects of Sample Size on Parametrizing a Taper Curve Equation and the Resultant Stem-Volume Estimates’. In: *Forests* 10.10, p. 848. doi: 10.3390/f10100848.
- Saglam, Serhun, Emrah Ozdemir, Ulas Yunus Ozkan, Tufan Demirel & Ender Makineci (2020). ‘Biomass estimation of aboveground tree components for Turkey oak (*Quercus cerris* L.) in south-eastern Turkey’. In: *Environmental Monitoring and Assessment* 192.7. doi: 10.1007/s10661-020-08386-z.
- Sankaran, M., N. P. Hanan, R. J. Scholes, J. Ratnam, D. J. Augustine, B. S. Cade, J. Gignoux, S. I. Higgins, X. Le Roux, F. Ludwig et al. (2005). ‘Determinants of woody cover in African savannas’. In: *Nature* 438.8, pp. 846–849. doi: 10.1038/nature04070.
- SASSCAL (2020). *SASSCAL WeatherNet*. URL: [www.sasscalweathernet.org](http://www.sasscalweathernet.org) (visited on 26/04/2021).
- Schepaschenko, Dmitry, Jérôme Chave, Oliver L. Phillips, Simon L. Lewis, Stuart J. Davies, Maxime Réjou-Méchain, Plinio Sist, Klaus Scipal, Christoph Perger, Bruno Herault et al. (2019). ‘The Forest Observation System, building a global reference dataset for remote sensing of forest biomass’. In: *Scientific Data* 6.1. doi: 10.1038/s41597-019-0196-1.
- SEOSAW (2020). ‘A network to understand the changing socio-ecology of the southern African woodlands (SEOSAW): Challenges, benefits, and methods’. In: *Plants, People, Planet*. doi: 10.1002/ppp3.10168.
- Solbrig, O. T., E. Medina & J. F. Silva (1996). *Biodiversity and Savanna Ecosystem Processes*. Berlin, Germany: Springer-Verlag.
- Srinivasan, Shruthi, Sorin Popescu, Marian Eriksson, Ryan Sheridan & Nian-Wei Ku (2015). ‘Terrestrial Laser Scanning as an Effective Tool to Retrieve Tree Level Height, Crown Width, and Stem Diameter’. In: *Remote Sensing* 7.2, pp. 1877–1896. doi: 10.3390/rs70201877.
- Staver, A. C., S. Archibald & S. A. Levin (2011). ‘The Global Extent and Determinants of Savanna and Forest as Alternative Biome States’. In: *Science* 334.6053, pp. 230–232. doi: 10.1126/science.1210465.
- Stevens, Nicola, Caroline E. R. Lehmann, Brett P. Murphy & Giselda Durigan (2017). ‘Savanna woody encroachment is widespread across three continents’. In: 23.1, pp. 235–244. doi: 10.1111/gcb.13409.
- Takoudjou, Stéphane Momo, Pierre Ploton, Bonaventure Sonké, Jan Hackenberg, Sébastien Griffon, Francois Coligny, Narcisse Guy Kamdem, Moses Libalah, Gislain II Mofack, Gilles Le Moguédec et al. (2017). ‘Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach’. In: *Methods in Ecology and Evolution* 9.4. Ed. by Sean McMahon, pp. 905–916. doi: 10.1111/2041-210x.12933.
- Thies, Michael, Norbert Pfeifer, Daniel Winterhalder & Ben G. H. Gorte (2004). ‘Three-dimensional reconstruction of stems for assessment of taper, sweep and lean based on laser scanning of standing trees’. In: *Scandinavian Journal of Forest Research* 19.6, pp. 571–581. doi: 10.1080/02827580410019562.
- Umbach, D. & K.N. Jones (2003). ‘A few methods for fitting circles to data’. In: *IEEE Transactions on Instrumentation and Measurement* 52.6, pp. 1881–1885. doi: 10.1109/tim.2003.820472.
- Wagner, Fabien Hubert, Matheus Pinheiro Ferreira, Alber Sanchez, Mayumi C.M. Hirye, Maciel Zortea, Emanuel Gloor, Oliver L. Phillips, Carlos Roberto de Souza Filho, Yosio Edemir Shimabukuro & Luiz E.O.C. Aragão (2018). ‘Individual tree crown delineation in a highly diverse tropical forest using very high resolution satellite images’. In: *ISPRS Journal of Photogrammetry and Remote Sensing* 145, pp. 362–377. doi: 10.1016/j.isprsjprs.2018.09.013.
- White, F. (1983). *The Vegetation of Africa: A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa*. Paris, France: UNESCO. doi: 10.2307/2260340.
- Xiao, Jingfeng, Frederic Chevallier, Cecile Gomez, Luis Guanter, Jeffrey A. Hicke, Alfredo R. Huete, Kazuhito Ichii, Wenjian Ni, Yong Pang, Abdullah F. Rahman et al. (2019). ‘Remote sensing of the terrestrial carbon cycle: A review of advances over 50 years’. In: *Remote Sensing of Environment* 233, p. 111383. doi: 10.1016/j.rse.2019.111383.