

Supplemental Material

An African Tree Crown–Stem Allometry Dataset for Monitoring Trees Outside Forests and Landscape Restoration

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FIELD GUIDE AND STANDARD MEASUREMENT PROTOCOL

Introduction

This document provides guidance for deploying field measurement activities to measure selected biophysical parameters of trees outside of forests (TOF). The aim of the field measurement scheme is twofold:

- 1) Collection of training datasets for developing an allometric model that predicts tree DBH from remote sensing crown CPA, which requires collecting field data on tree DBH matched exactly with the remote sensing CPA for the same tree. The collection of field CPA and other selected parameters may also be included,
- 2) Validation of remote sensing mapping of individual, isolated trees outside of forests and clusters of trees not forming forests.

General Overview

The protocol is a standard operating procedure for field measurements, data collection, and recording for carbon stock estimation for trees outside of forests (TOF) in 1) landscapes and 2) intervention areas, including planted trees, isolated trees, plantations, and agroforestry and other individual tree-based activities. Field measurements are part of an effort to map TOF at site scale and extensive landscape. The protocol captures data and information required to collect a large sample of individual tree allometric parameters to calibrate CA-DBH allometric models to enable the use of CPA measurements from VHR and machine learning to estimate carbon for individual trees. The field measurements can also be used with existing Allometric models to estimate carbon stock at the tree and plot levels. These steps are required for developing baseline carbon stock estimates and for annual reporting of carbon sequestration for carbon offset projects that meet the compliance standards of carbon markets.

The protocol follows two modes of field deployment, which are to be done at both the landscape and site scales. The first modality for field deployment is site verification. Here, the team inspects the

landscape and gathers observations, informing the analysis and field measurement. Detailed photographic and documentary information is compiled about landscape types, site conditions, and sites where restoration is taking place and making notes of the ecological context. This Modality supports site verification efforts and helps verify remote sensing tree maps of the landscape.

The second modality for field deployment is actual measurements using sample plots in which parameters that relate tree characteristics, usually allometric scaling parameters, to tree and stand biomass, which can then be transformed into tree or tree-cover carbon stocks. The focus on measurements is on standing live AGB.

The method used in this protocol is based on mapping, in which field measurements are used to gather data for developing a model that inter-relates allometric parameters from field and remote sensing. This method is ideal for mapping individual trees outside of forests for limited areas or landscape-wide areas. The method produces a simple regression model that allows remote sensing mapping of individual tree canopies as Crown Projected Area (CPA) to be related to a standard allometric parameter of stem diameter (DBH). This, in turn, allows the use of existing standard allometric equations based on DBH to compute individual tree carbon stocks. This mapping is applied to very high-resolution remote sensing data to map carbon stock in large landscapes at the tree level. The mapping of individual tree CPA is made using machine learning image segmentation analysis.

Carbon pools measured and what is not measured

Here we discuss the ecological objects or landscape features that will not be measured. The measurements do not include shrubs, as these are usually not considered important contributors to biomass compared to trees. To the extent that shrubs are dominant in the landscape, they should be tallied or estimated in terms of location and cover during site verification. Belowground live biomass will not be measured directly as it is incredibly labor-intensive and time-consuming. Instead, a standard root-to-shoot ratio of 0.26 shall be used. Soil C will not be measured. It will be assumed to be de minimis or conservative. By conservative we mean that while soil organic may have a contribution to carbon storage and sequestration, we shall forgo its consideration in carbon reporting. Similarly, unless important, litter will not be measured. Also, standing dead and lying dead wood will not be measured. Individual seedling counts will be emphasized over biomass estimation. Later, we shall consider using heights to measure a proxy for biomass. Repeated counts will be used to estimate mortality.

Data tabulation sheet

Data collected in the field at each sample plot shall be recorded in a standard form. The form is in an Excel spreadsheet format. This standard form can be printed as a hard copy on write-in-the-rain paper or downloaded to a tablet or laptop. The latter is preferred. Store digital data securely and backup regularly.

Equipment list

The essential equipment needed for field measurements is shown in the list below.

Equipment	Primary Use
Diameter tape	Measure DBH
50-meter tape	Measure crown diameters
GPS device	Record tree location
GPS camera	Capture geotagged images

Laptop with satellite data	Navigation to sample plot
Hypsometer/Clinometer	total tree height
Compass	Navigation and orientation
Data sheets/ Digital Tablets	Record field data
VHR Centroid 1-ha plots	Tree identification for measurement
Tree identification guide	Tree species identification

Team composition and roles

A team of 5 to 7 people will be needed to take measurements in the field. The team should include:

1. Two individuals to handle the 50 m tape for measuring crown areas.
2. One person to measure Diameter at Breast Height (DBH).
3. One person to use a GPS for locating the plot center and marking tree locations.
4. One person to capture geotagged landscape photos.
5. One person to record the field measurements.
6. One person may be assigned to measure tree height if necessary.

As time goes on, team members may adjust these assignments to improve efficiency or adapt to changing circumstances.

Pre-assessment and preparation

1. Conduct a landscape selection exercise to identify large landscapes to do the work. The landscape selection exercise can be done using Google Earth engine or any remote sensing software
2. Remote sensing mapping of those areas of TOF at a broad scale at a high-resolution using Landsat or Sentinel-2 data (predominantly Sentinel-2).
3. Identification of a large sample of 1 ha plots for measurement of tree allometric parameters in areas of high density TOF, using the spatial and crown size characteristics from the remote sensing to guide sample locations and sample allocation.
4. Conduct a site assessment. Upon arrival at the site, the site may not be a satisfactory location if there are problems with any of the following: topography is too steep or inaccessible, the site does not fulfill appropriate strata and/or land cover classification, there are some forms of hazards that would affect safety, not all the plots would be inside a forest or other issues. If the site is rejected, prepare a report that documents the rationale for rejecting it. Take a suitable number of photos to document the site conditions.
5. If the plots are to be measured, fill out metadata entries in the data sheet and set up measurements.
6. To proceed with measurements, allocate all the equipment to the appropriate team member responsible for that element of the measurement protocol.

The site verification method

This method uses geotagged photos to document the local tree and vegetation cover context well. Geotagged photos contain embedded geographical information that identifies the location where the photo was taken. During image-capturing, geotagging associates the captured location data with the photo. This geographical metadata often comes in GPS coordinates, which provide precise details like latitude and longitude. The geolocation on the photos allows users to organize and share their photos

based on the locations where they were taken. To automatically add geotagging to your photos, ensure your phone's location services are turned on. The Geotagged photos are a ground-truthing effort that will be used later to interpret the landscape.

For all Trees Outside of Forest (TOF) plots, photos are captured from the circular 1-ha plot center in four cardinal directions: North, East, West, and South. Each photo will be labeled with the Project ID, Plot ID, and the direction from which the picture is taken. Here is an example:

- If the Project ID is EPZ, the Plot ID is 18, and the photo is taken from the center facing North, label it EPZ 18 N.
- If the photo is taken from the center facing East, label it as EPZ 18 E.
- If the photo is taken from the center facing West, label it as EPZ 18 W.
- If the photo is taken from the center facing South, label it as EPZ 18 S.

This labeling system ensures unambiguous identification of each geotagged photo based on the Project ID, Plot ID, and the direction in which it was taken from the center of the TOF plot.

Here is a link to an ArcGIS web map developed with the geotagged photos taken for the AFR100 projects in Ghana, Kenya, and Rwanda: <https://arcg.is/1TuiKL1>.

Method for individual tree measurement

A pre-determined centroid 1 ha plot is measured here. The team should identify the centroid of pre-specified 1-ha plots within the project landscape. Each allocated sample plot shall be located in the field using the plot centroid and GPS. These centroids are mapped before fieldwork but can also be reasonably selected in the field. When using prior maps of plots from VHR remote sensing data, the field analyst shall ensure direct matching between the trees in the sample plots and the same trees identified in the VHR data. Field measurements of the crown area should match with the same tree in the VHR data map of CPA.

Field crews should measure the first tree north of the plot centroid within the plot and then measure all trees moving clockwise toward the East. The following measurements need to be made in the field and noted precisely where also identified in the VHR remote sensing map:

- 1) Plot number and plot features notes
- 2) Date
- 3) Tree locations, GPS, and identified on the VHR map
- 4) Tree identification number which includes the tree # and Plot #, and identified on the VHR map
- 5) Tree species name
- 6) DBH (cm)
- 7) Crown Area (m²) This is measured using the long-axis crown diameter and its perpendicular diameter.
- 8) Tree height, if possible.

Tree Measurements. All trees over a minimum diameter, typically 5 cm, in a plot must be measured. The standard parameters for all trees measured within the plot include genus, species, diameter at breast height (1.3 m), two crown diameters, and tree location. Additional parameters include total

height.

DBH: Measure DBH at 1.3 meters above ground level using a calibrated diameter tape. The DBH tape must be used correctly to ensure measurement consistency. The field crew should measure where 1.3 m is on their body or use a 1.3 m long staff to identify the correct height to measure the diameter of every tree. Always measure on the uphill side if the tree is on a slope. If the tree is leaning, the DBH tape must be wrapped to be perpendicular to the main axis of the trunk (not parallel to the ground). If the tree is forked below 1.3 m, measure the two trunks as separate trees. If the tree forks above 1.3 m, measure the DBH of the main stem (unless there is an unusual bulge right at 1.3m).

Crown Diameter: Measure the longest and perpendicular crown diameters using a 50-meter tape. The longest crown diameter is the maximum crown diameter (from dripline to dripline) as determined by visual inspection of the tree. The perpendicular crown diameter is measured at 90° to the maximum crown diameter. A simple method to ensure vertical upward sighting directly under the true crown edge (dripline) is to look through a right-angle prism or a clinometer that identifies 90° when standing under the crown edge. Measure the crown diameter (m) from crown edge to crown edge. The crown area is estimated by using the formula for the area of an ellipse (π * half of the maximum diameter * half of the diameter at 90°).

Tree Height: Measure using a hypsometer or clinometer. Clinometers are low-cost tools that measure one of several parameters (percent, degrees, secant, etc.) used to calculate tree height based on that measurement and a known horizontal distance away from the base of the tree. Consult equipment manuals for the correct methods to measure tree height using a clinometer. Hypsometers are more expensive electronic devices that use lasers to measure tree height and other parameters. Consult specific equipment manuals for the correct methods to measure tree height using a hypsometer.

Tree Species Identification: Identify genus and species based on field guides and botanical references.

Tree location: The geographic location of all measured trees should be recorded with a global positioning system device (GPS) to allow for geographic information system analysis (GIS) and possible return to the site. The GPS should be calibrated—record GPS coordinates in decimal degrees or UTM format for spatial referencing. The center coordinates of the plot should also be recorded.

SUPPLEMENTAL FIGURES AND TABLES

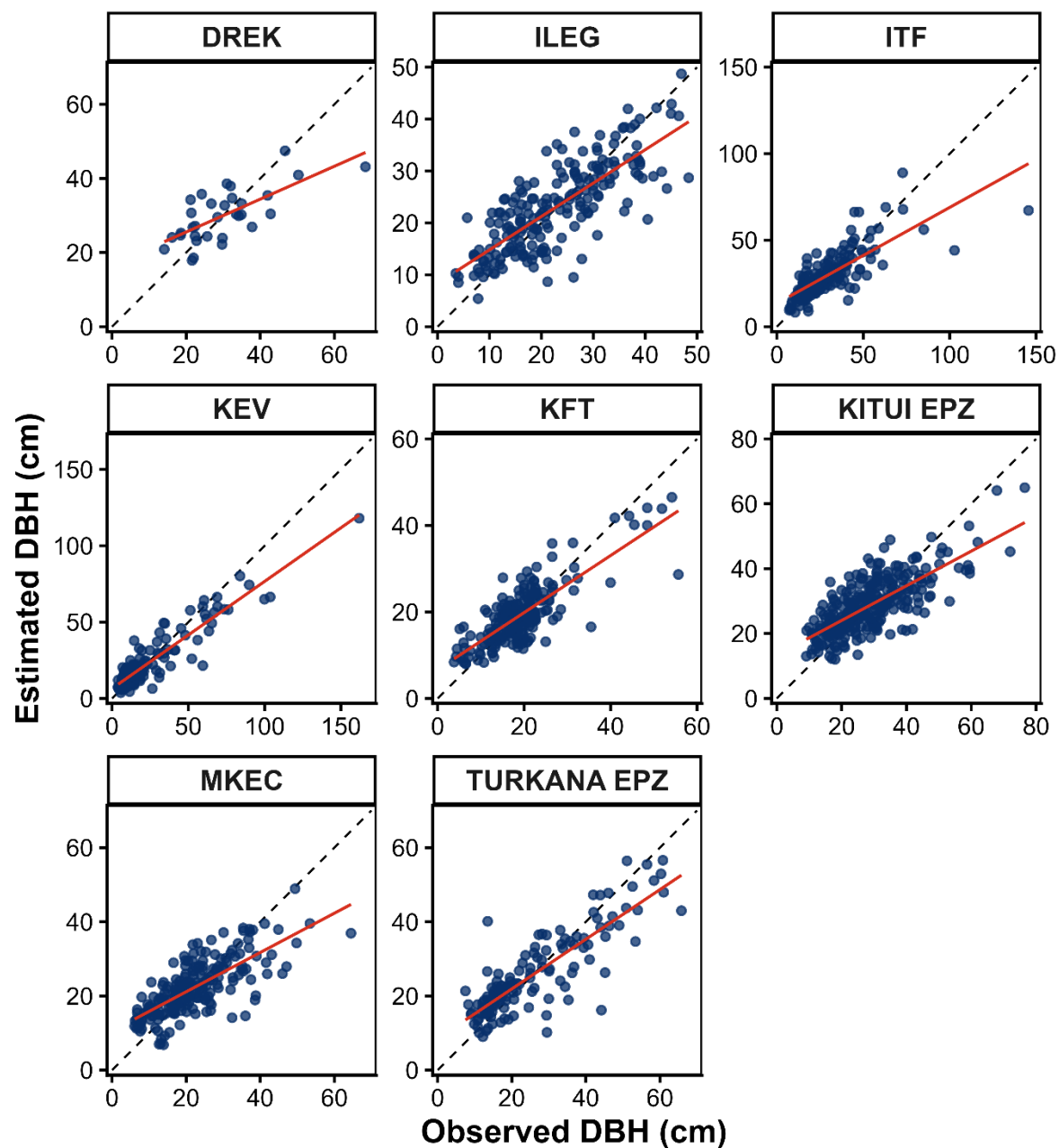


Figure S1: Observed vs. predicted DBH predictive accuracy for site-specific allometric models in Kenya. The red line shows model fit, and the dashed black line represents the 1:1 reference

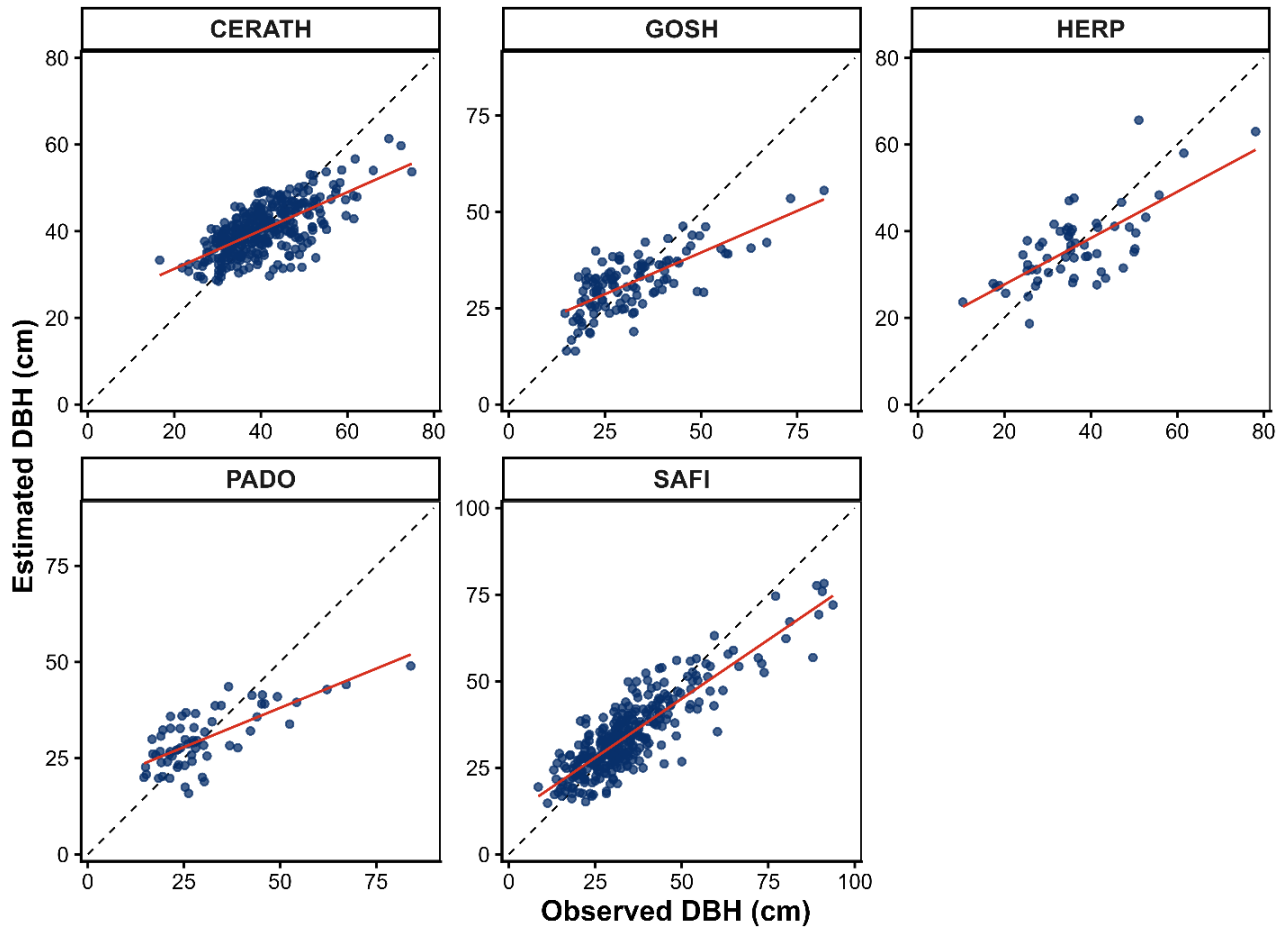


Figure S2: Observed vs. predicted DBH predictive accuracy for site-specific allometric models in Ghana. The red line shows model fit, and the dashed black line represents the 1:1 reference.

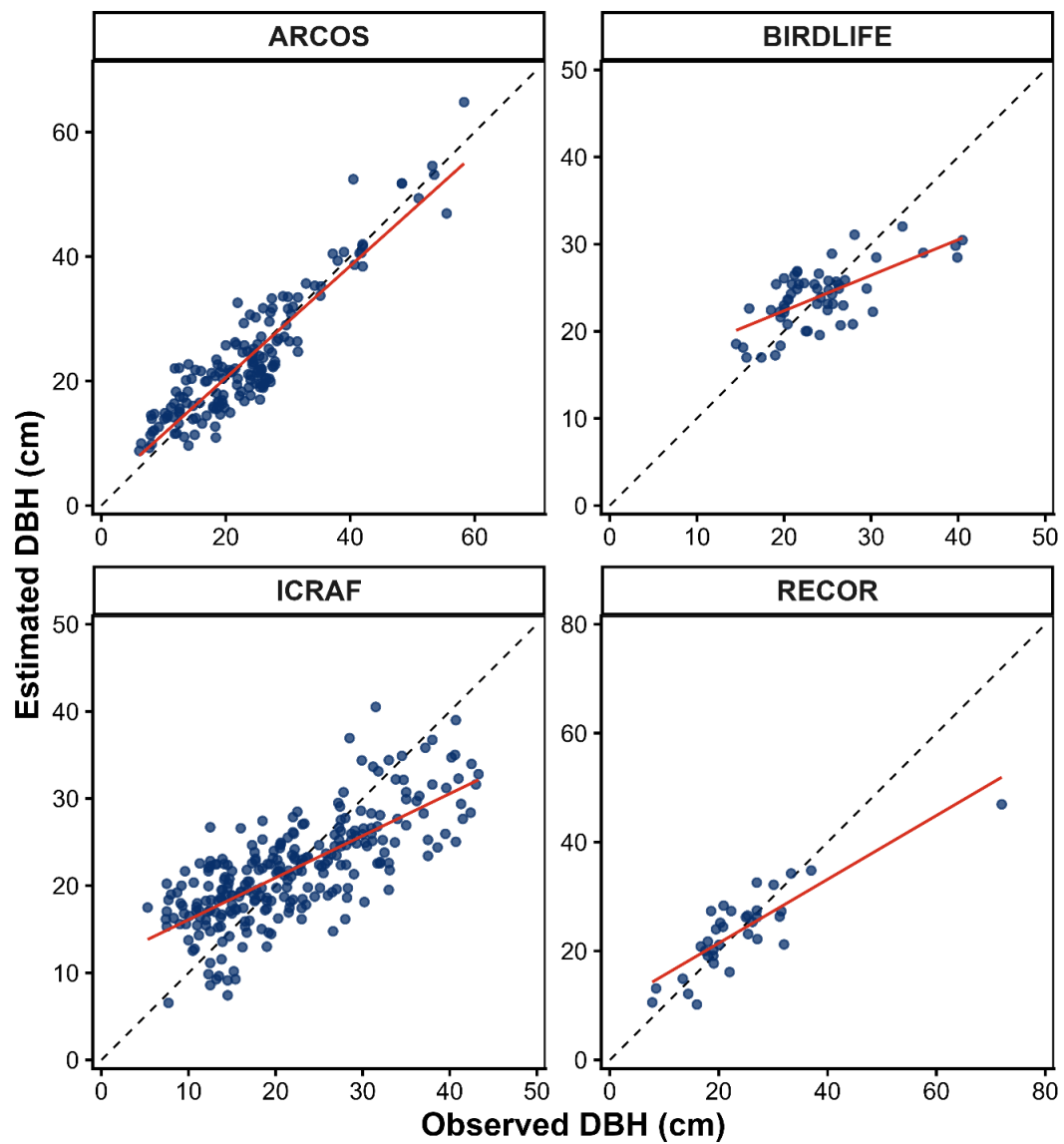


Figure S3: Observed vs. predicted DBH predictive accuracy for site-specific allometric models in Rwanda. The red line shows model fit, and the dashed black line represents the 1:1 reference.

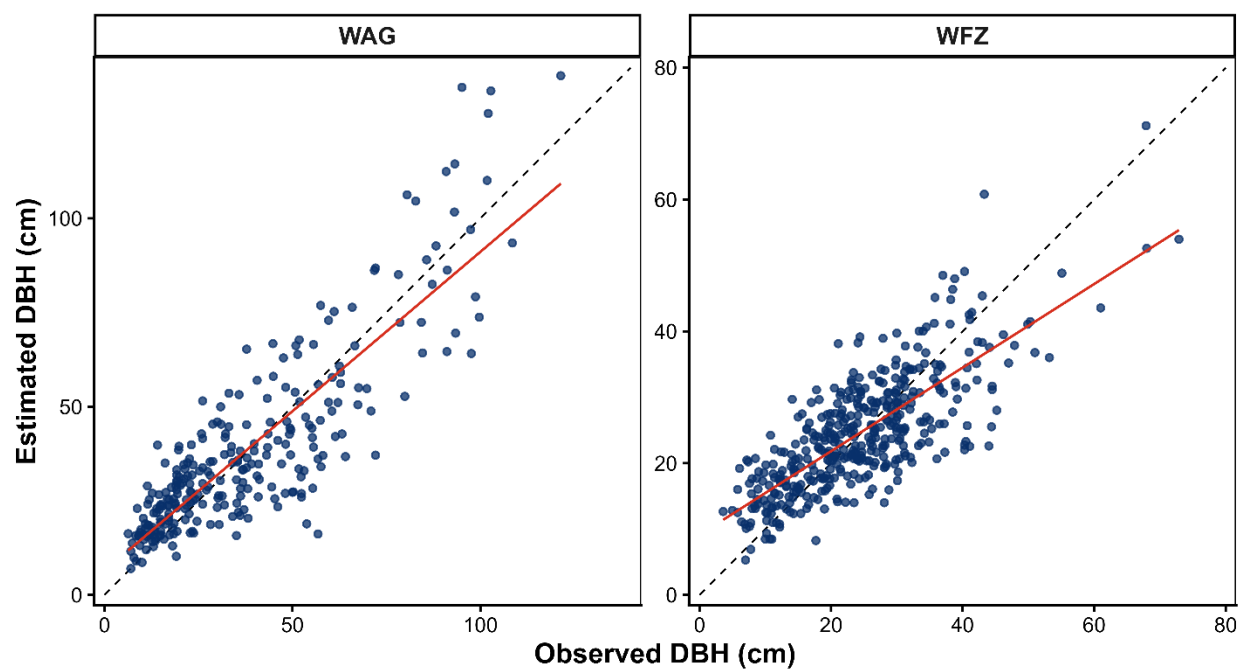


Figure S4: Observed vs. predicted DBH predictive accuracy for site-specific allometric models in Malawi. The red line shows model fit, and the dashed black line represents the 1:1 reference.

Table S1: Plot-level land cover classes assigned using the FAO Land Cover Classification System (LCCS). The table includes site and plot identifiers, coordinates, the LCCS code identifying each land cover class, the hierarchical classification level, and the user-defined land cover label.

Site ID	Plot ID	Latitude	Longitude	LCC Code	LCC Level	LCC Own Label
KFT	1	-0.92451	36.57189	21450	A4A20B3	Closed to open shrubland
KFT	2	-0.92536	36.57106	21450	A4A20B3	Closed to open shrubland
KFT	8	-0.97843	36.60355	11498	A3XXXXXXD1	Rainfed cropland
KFT	10	-0.98294	36.60305	11498	A3XXXXXXD1	Rainfed cropland
KFT	11	-0.98388	36.60346	11498	A3XXXXXXD1	Rainfed cropland
KFT	12	-0.95348	36.60472	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
KFT	13	-0.99009	36.60364	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
KFT	14	-0.9919	36.60427	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
KFT	16	-0.97463	36.60159	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
KFT	17	-0.97386	36.59995	11498	A3XXXXXXD1	Rainfed cropland
KFT	18	-0.98303	36.60422	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
KFT	20	-0.97929	36.60299	11498	A3XXXXXXD1	Rainfed cropland
KITUI EPZ	1	-0.70097	38.08262	21450	A4A20B3	Closed to open shrubland
KITUI EPZ	2	-0.73339	38.09898	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	3	-0.76833	38.09704	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	4	-0.86754	38.0748	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	5	-0.9343	38.03426	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	18	-0.46723	38.29773	21450	A4A20B3	Closed to open shrubland
KITUI EPZ	19	-0.43443	38.35596	21450	A4A20B3	Closed to open shrubland
KITUI EPZ	20	-0.76765	38.32855	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	21	-0.76819	38.33586	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	22	-0.75021	38.4825	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	23	-0.78376	36.33695	7001 // 8001	A1 // A1	Water bodies
KITUI EPZ	24	-0.78389	38.33288	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KITUI EPZ	25	-0.76791	38.02053	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
TURKANA EPZ	0	3.12248	35.57959	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	1	3.11677	35.57713	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	2	3.11813	35.57554	11	B16	Bare areas

TURKANA EPZ	3	3.111875	35.57347	11	B16	Bare areas
TURKANA EPZ	4	3.11776	35.56585	11	B16	Bare areas
TURKANA EPZ	5	3.12469	35.55538	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	6	3.12723	35.56127	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	7	3.07527	35.50831	11	B16	Bare areas
TURKANA EPZ	8	3.07476	35.50578	11	B16	Bare areas
TURKANA EPZ	8	3.07476	35.50578	11	B16	Bare areas
TURKANA EPZ	9	3.07284	35.50793	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	10	3.4446	35.48922	21454 // 21465	A2A20B4 // A7A20	Closed to open herbaceous vegetation (or lichen and mosses)
TURKANA EPZ	11	3.04344	35.49119	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	12	3.04584	35.48577	20049 // 20058	A1A14 // A2A14	Sparse vegetation
TURKANA EPZ	13	3.0526	35.54762	11	B16	Bare areas
TURKANA EPZ	14	3.05472	35.54841	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
TURKANA EPZ	15	3.05395	35.5495	11	B16	Bare areas
TURKANA EPZ	16	3.09159	35.59356	11	B16	Bare areas
TURKANA EPZ	17	3.0586	35.5026	20049 // 20058	A1A14 // A2A14	Sparse vegetation
MKEC	1	-0.41378	37.62849	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
MKEC	2	-0.41183	37.63318	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
MKEC	3	-0.41664	37.63949	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
MKEC	21	-0.50503	37.63293	21497- 121340	A3A20B2XXD1E2- A21	Closed (>40%) broadleaved deciduous forest
MKEC	22	-0.50501	37.63146	21497- 121340	A3A20B2XXD1E2- A21	Closed (>40%) broadleaved deciduous forest
KEV	5	-0.77165	36.66786	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KEV	4	-0.77337	36.66913	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KEV	2	-0.77609	36.67283	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
KEV	15	-0.95497	36.62051	21497- 121340	A3A20B2XXD1E2- A21	Closed (>40%) broadleaved deciduous forest
KEV	16	-0.9566	36.6173	21497- 121340	A3A20B2XXD1E2- A21	Closed (>40%) broadleaved deciduous forest

KEV	18	-0.96346	36.6197	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
KEV	20	-0.99316	36.65019	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
ILEG	1	0.051806	34.17186	21450	A4A20B3	Closed to open shrubland
ILEG	2	0.050817	34.175	0003 / 0004	A11 / A12	Mosaic cropland vegetation
ILEG	7	0.048614	34.18848	0003 / 0004	A11 / A12	Mosaic cropland vegetation
ILEG	9	0.179036	34.25901	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ILEG	11	0.177828	34.25899	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ILEG	15	0.186742	34.24739	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ILEG	16	0.187625	34.24856	0003 / 0004	A11 / A12	Mosaic cropland vegetation
ILEG	21	0.132633	34.42409	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ITF	0	2.025613	38.02832	11	B16	Bare areas
ITF	1	2.26328	38.02796	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	2	2.2596	38.03485	11	B16	Bare areas
ITF	3	2.226404	38.03099	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	4	2.28562	38.08347	11	B16	Bare areas
ITF	5	2.28284	38.07953	11	B16	Bare areas
ITF	6	2.24011	38.00688	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	7	2.24448	38.00611	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	8	2.23952	38.00452	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	9	2.23173	38.99111	20049 // 20058	A1A14 // A2A14	Sparse vegetation
ITF	10	2.23207	37.99728	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	11	2.22436	37.99415	21446 // 21450-121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland

ITF	12	2.21595	37.97934	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	14	2.222	37.97464	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	15	2.21068	37.89942	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
ITF	16	2.212934	37.88629	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
DREK	0	0.33501	39.59417	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	1	0.33364	39.59503	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	2	0.33471	39.59236	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	3	0.34365	39.59469	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	4	0.32303	39.58889	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	5	0.32311	39.5858	20049 // 20058	A1A14 // A2A14	Sparse vegetation
DREK	7	0.29367	39.57574	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
DREK	8	0.29048	39.57427	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
DREK	10	0.29262	39.57085	21446 // 21450- 121340 / 21454	A3A20B2 // A4A20B3-A21 / A2A20B4	Mosaic forest or shrubland/grassland
SAFI	0	8.623288	-2.27497	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
SAFI	1	8.622877	-2.27316	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
SAFI	2	5.002434	-2.2808	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
SAFI	3	8.014897	-2.36966	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
SAFI	4	8.011795	-2.36412	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
SAFI	9	8.65218	-2.29165	21450	A4A20B3	Closed to open shrubland
SAFI	30	8.675519	-2.29881	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
SAFI	31	8.655367	-2.29332	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland

GOSH	4	5.159485	-1.6588	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
GOSH	5	5.164624	-1.66413	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
GOSH	30	5.267874	-2.73687	21496 // 21497- 15048	A3A20B2XXD1E1 // A3A20B2XXD1E2- E4	Closed to open broadleaved evergreen or semi-deciduous forest
GOSH	31	5.214045	-2.72999	21496- 121340 // 21497- 129401	A3A20B2XXD1E1- A21 // A3A20B2XXD1E2- A21E4	Closed (>40%) broadleaved evergreen or semi-deciduous forest
GOSH	34	5.238624	-1.62718	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
GOSH	35	5.240705	-1.62722	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
CERATH	4	10.47746	-0.50216	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	8	10.47753	-0.49615	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	9	10.42041	-0.61871	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	10	10.42497	-0.62297	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	11	10.42746	-0.60994	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	31	10.521	-0.39233	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	32	10.42455	-0.53789	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	33	10.41601	-0.55181	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	34	10.41543	-0.54807	0003 / 0004	A11 / A12	Mosaic cropland vegetation
CERATH	35	10.41402	-0.54744	0003 / 0004	A11 / A12	Mosaic cropland vegetation
PADO	16	6.988725	-1.94489	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
PADO	17	6.991142	-1.94617	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
PADO	18	6.990522	-1.94389	21445 / 0003	A3A20 / A11	Mosaic forest/cropland
HERP	31	6.861308	0.449281	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
HERP	30	6.844058	0.446362	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
HERP	32	6.842253	0.444961	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
HERP	33	6.84033	0.431761	21496 // 21497- 15048	A3A20B2XXD1E1 // A3A20B2XXD1E2- E4	Closed to open broadleaved evergreen or semi-deciduous forest
ACROS	0	-2.36767	30.52419	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
ACROS	1	-2.37241	30.52514	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland

ACROS	2	-2.36931	30.52428	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
ACROS	6	-2.38331	30.52612	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	7	-2.38664	30.53568	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
ACROS	8	-2.39449	30.5332	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
ACROS	10	-2.37089	30.78949	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	13	-2.36787	30.78466	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	14	-2.36879	30.78193	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	16	-2.3658	30.77767	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	17	-2.36431	30.77707	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	18	-2.35849	30.77842	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ACROS	19	-2.35698	30.77766	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
BIRDLIFE	1	-2.5677	29.15842	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
BIRDLIFE	2	-2.56627	29.16002	21496 // 21497-15048	A3A20B2XXD1E1 // A3A20B2XXD1E2-E4	Closed to open broadleaved evergreen or semi-deciduous forest
BIRDLIFE	3	-2.56879	29.15974	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
BIRDLIFE	4	-2.56823	29.16046	21497-121340	A3A20B2XXD1E2-A21	Closed (>40%) broadleaved deciduous forest
BIRDLIFE	5	-2.57262	29.16091	20135-3012 // 20134-3012	A3A11B2XXD2E2-A13 // A3A11B2XXD2E1-A13	Open (15-40%) needle leaved deciduous or evergreen forest
BIRDLIFE	10	-2.57973	29.1551	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
BIRDLIFE	19	-2.59144	29.17652	11498	A3XXXXXXD1	Rainfed cropland
ICRAF	0	-1.95143	30.61485	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	1	-1.43266	30.43243	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	2	-1.94865	30.61565	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	3	-1.43421	30.43629	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	4	-1.43249	30.44529	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	5	-1.43155	30.44518	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	6	-1.43287	30.44742	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	7	-1.43856	30.4571	21450	A4A20B3	Closed to open shrubland
ICRAF	9	-1.436	30.46566	21450	A4A20B3	Closed to open shrubland

ICRAF	10	-1.94851	30.61034	21450	A4A20B3	Closed to open shrubland
ICRAF	11	-1.94837	30.60525	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	12	-1.4224	30.46739	21454 // 21446 // 21450	A2A20B4 // A3A20B2 // A4A20B3	Mosaic grassland/forest or shrubland
ICRAF	13	-1.95103	30.60303	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	14	-1.95567	30.60595	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	15	-1.45969	30.4502	21450	A4A20B3	Closed to open shrubland
ICRAF	16	-1.45969	30.4502	21450	A4A20B3	Closed to open shrubland
ICRAF	17	-1.96215	30.61279	21450	A4A20B3	Closed to open shrubland
ICRAF	20	-1.46337	30.43385	21450	A4A20B3	Closed to open shrubland
ICRAF	21	-1.45615	30.43794	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
ICRAF	22	-1.95346	30.60351	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
RECOR	8	-2.25181	30.25663	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
RECOR	9	-2.25064	30.25601	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
RECOR	12	-2.22154	30.22063	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
RECOR	13	-2.22078	30.21993	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	1	-11.5221	33.87885	21450	A4A20B3	Closed to open shrubland
WFZ	3	-11.4817	33.8545	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	5	-11.4779	33.85831	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	6	-11.5236	33.87713	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
WFZ	8	-11.4721	33.85628	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	9	-11.4731	33.8605	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	11	-11.4819	33.85075	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WFZ	13	-11.5101	33.88316	21450	A4A20B3	Closed to open shrubland
WFZ	14	-11.5074	33.88432	21450	A4A20B3	Closed to open shrubland
WFZ	15	-11.5004	33.8772	21450	A4A20B3	Closed to open shrubland
WFZ	16	-11.4689	33.86034	0004 // 0003	A12 // A11	Mosaic vegetation/cropland
WAG	3	-13.9608	34.38347	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	4	-13.961	34.37796	21450	A4A20B3	Closed to open shrubland
WAG	11	-13.9366	34.35311	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	14	-13.9447	34.35796	20132- 3012	A3A11B2XXD1E2- A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	15	-13.946	34.36228	21497- 15045	A3A20B2XXD1E2- E3	Closed to open (>15%) mixed broadleaved deciduous

WAG	16	-13.9487	34.36303	20132-3012	A3A11B2XXD1E2-A13	and needle-leaved evergreen forest Open (15-40%) broadleaved deciduous forest /woodland
WAG	17	-13.9485	34.36475	21497-15045	A3A20B2XXD1E2-E3	Closed to open (>15%) mixed broadleaved deciduous and needle-leaved evergreen forest
WAG	18	-13.9551	34.3721	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	20	-13.9585	34.37673	21454 // 21446 // 21450	A2A20B4 // A3A20B2 // A4A20B3	Mosaic grassland/forest or shrubland
WAG	22	-13.9731	34.32383	21450	A4A20B3	Closed to open shrubland
WAG	24	-13.9665	34.32661	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	26	-13.9816	34.31073	20132-3012	A3A11B2XXD1E2-A13	Open (15-40%) broadleaved deciduous forest /woodland
WAG	27	-13.9826	34.30795	21454 // 21446 // 21450	A2A20B4 // A3A20B2 // A4A20B3	Mosaic grassland/forest or shrubland

Table S2: Descriptive statistics of DBH, crown long diameter (Crown_L), and crown perpendicular diameter (Crown_P) across each sampling site. The values show the sample size (n), Minimum (Min), mean, and maximum (Max) value of the observations at each site in Kenya, Ghana, Rwanda, and Malawi.

Site ID	n	DBH (cm)			Crown_L (m)			Crown_P (m)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
DREK	32	14.1	30	68.4	5.3	10.7	19	4.8	9.6	18
ITF	157	7.2	30.4	145.6	3	9.8	27.1	1.9	8.2	25.3
KITUI EPZ	291	9.1	28.6	76.5	3	9.6	27	2.6	8.3	25
TURKANA EPZ	135	7.5	25.8	65.8	3.1	9.7	19.7	3.4	9.5	22.1
MKEC	204	6.1	22.2	64.5	1.7	6.5	14.8	1.2	5.5	14.5
ILEG	201	3.5	22.8	48.4	1.5	7.5	16.1	1.4	6.6	15.5
KEV	145	4	23.5	162	1.6	6.3	25.5	1.5	5.5	17.5
KFT	219	3.8	19.1	55.7	2.4	7	20.5	2	6.3	18
CERATH	333	16.6	40.3	74.9	6	10.2	17.6	5.3	9.3	17.4
SAFI	325	8.5	34.4	93.7	2.6	7.3	21	2	6.4	18.5
HERP	58	10.4	36.2	78.1	4.2	10.5	22	3.7	9.5	22
GOSH	116	14.6	31.6	82	3.6	9.5	17.6	3.1	8.6	17.2
PADO	63	14.6	30.2	84	3.1	7.9	15.6	2.5	7.1	15.2
RECOR	35	7.8	23.7	72	2.3	6.8	15.5	2.4	6.4	14.6
ARCOS_	165	6.1	23.1	58.3	1.9	5.9	16.8	1.7	5.5	15.4
BIRDLIFE	57	14.5	24	40.5	1.4	3.2	6.1	1.3	2.9	5.6
ICRAF	264	5.3	21.7	43.3	1.2	6.7	15.9	1	6.1	15.5
WAG	269	6.3	37.6	121.4	2.2	9.2	29.5	1.7	7.9	26
WFZ	419	3.6	24.4	72.9	1.5	6.6	18	1.5	5.8	15.7

Table S3: Site-specific allometric model performance across different DBH ranges in the sampling sites in Kenya, Ghana, Rwanda, and Malawi. DBH is modeled as a power function of Crown Area (CA), and a and b are the allometric parameters. Models are assessed using R², RMSE, %RMSE, Bias, and percent error (Bias%).

Site ID	DBH range	n	a	b	R2	RMSE	RMSE%	Bias	Bias%	P-value
DREK	Full	32	5.613	0.376	0.50	7.89	26.32	0.01	0.03	<0.001
DREK	≤60	31	6.767	0.328	0.45	6.53	22.73	-0.06	-0.21	<0.001
DREK	≤50	30	7.550	0.300	0.39	6.24	22.28	-0.07	-0.25	<0.001
DREK	≤40	27	9.498	0.237	0.25	5.45	20.75	-0.08	-0.29	<0.001
ILEG	Full	201	4.120	0.457	0.61	6.33	27.81	-0.25	-1.08	<0.001
ILEG	≤60	201	4.120	0.457	0.61	6.33	27.81	-0.25	-1.08	<0.001
ILEG	≤50	201	4.120	0.457	0.61	6.33	27.81	-0.25	-1.08	<0.001
ILEG	≤40	191	4.274	0.442	0.60	5.79	26.73	-0.24	-1.12	<0.001
ITF	Full	157	3.680	0.498	0.58	11.72	38.54	0.10	0.32	<0.001
ITF	≤60	150	4.118	0.465	0.58	8.00	28.75	-0.13	-0.46	<0.001
ITF	≤50	143	4.392	0.444	0.54	7.48	28.23	-0.14	-0.52	<0.001
ITF	≤40	123	4.311	0.437	0.54	6.06	25.70	-0.06	-0.27	<0.001
KEV	Full	145	2.224	0.663	0.85	10.08	42.79	0.58	2.44	<0.001
KEV	≤60	130	2.856	0.562	0.59	7.93	46.72	0.18	1.07	<0.001
KEV	≤50	125	3.120	0.520	0.57	6.35	41.18	0.08	0.49	<0.001
KEV	≤40	121	3.400	0.482	0.50	5.84	40.32	0.02	0.17	<0.001
KFT	Full	219	4.458	0.407	0.64	4.86	25.43	-0.14	-0.74	<0.001
KFT	≤60	219	4.458	0.407	0.64	4.86	25.43	-0.14	-0.74	<0.001
KFT	≤50	216	4.630	0.394	0.61	4.43	23.80	-0.17	-0.91	<0.001
KFT	≤40	211	4.846	0.379	0.46	4.33	24.06	-0.19	-1.03	<0.001
KITUI EPZ	Full	291	5.835	0.378	0.55	7.84	27.46	-0.04	-0.15	<0.001
KITUI EPZ	≤60	287	6.074	0.367	0.49	7.65	27.34	-0.06	-0.22	<0.001
KITUI EPZ	≤50	276	6.640	0.340	0.43	7.05	26.23	-0.09	-0.34	<0.001
KITUI EPZ	≤40	247	7.461	0.300	0.39	6.03	24.22	-0.09	-0.37	<0.001
MKEC	Full	204	5.006	0.434	0.55	6.89	31.05	-0.09	-0.41	<0.001
MKEC	≤60	203	5.089	0.428	0.54	6.63	30.16	-0.11	-0.51	<0.001
MKEC	≤50	202	5.149	0.423	0.53	6.57	30.09	-0.12	-0.54	<0.001
MKEC	≤40	193	5.489	0.397	0.49	5.95	28.67	-0.14	-0.66	<0.001
TURKANA EPZ	Full	135	2.528	0.530	0.72	7.42	28.81	0.02	0.07	<0.001
TURKANA EPZ	≤60	131	2.716	0.510	0.68	7.17	29.07	0.00	0.01	<0.001
TURKANA EPZ	≤50	124	3.037	0.480	0.58	6.98	30.32	0.00	0.01	<0.001
TURKANA EPZ	≤40	110	3.765	0.414	0.46	5.93	29.18	0.00	-0.02	<0.001
CERATH	Full	333	8.683	0.354	0.46	6.39	15.87	0.00	-0.01	<0.001
CERATH	≤60	325	9.786	0.325	0.38	6.06	15.28	-0.02	-0.04	<0.001
CERATH	≤50	290	11.963	0.271	0.31	5.20	13.70	-0.02	-0.06	<0.001
CERATH	≤40	184	13.580	0.223	0.31	3.43	10.06	-0.02	-0.06	<0.001
GOSH	Full	116	4.996	0.436	0.52	8.69	27.49	0.12	0.38	<0.001
GOSH	≤60	112	6.103	0.383	0.41	7.64	25.30	0.03	0.10	<0.001
GOSH	≤50	107	6.838	0.350	0.39	6.77	23.26	0.01	0.02	<0.001

GOSH	≤40	92	9.218	0.262	0.26	5.62	21.10	-0.02	-0.06	<0.001
HERP	Full	58	7.235	0.366	0.51	8.15	22.55	-0.19	-0.51	<0.001
HERP	≤60	56	8.127	0.337	0.36	7.88	22.55	-0.21	-0.59	<0.001
HERP	≤50	51	8.651	0.317	0.27	7.32	22.00	-0.19	-0.57	<0.001
HERP	≤40	40	8.070	0.315	0.38	5.26	17.45	-0.17	-0.56	<0.001
PADO	Full	63	8.397	0.330	0.53	9.39	31.13	0.16	0.54	<0.001
PADO	≤60	60	10.418	0.263	0.39	7.54	26.84	0.02	0.08	<0.001
PADO	≤50	58	11.215	0.237	0.38	6.78	24.88	0.00	0.01	<0.001
PADO	≤40	51	15.401	0.131	0.15	5.33	21.49	-0.03	-0.14	<0.001
SAFI	Full	325	8.334	0.390	0.74	7.33	21.32	0.03	0.08	<0.001
SAFI	≤60	308	9.434	0.349	0.62	6.21	19.41	-0.07	-0.23	<0.001
SAFI	≤50	290	10.211	0.321	0.52	5.85	19.13	-0.09	-0.30	<0.001
SAFI	≤40	247	11.229	0.282	0.42	5.16	18.28	-0.09	-0.32	<0.001
ARCOS	Full	165	2.653	0.511	0.83	4.26	18.44	-0.20	-0.86	<0.001
ARCOS	≤60	165	2.653	0.511	0.83	4.26	18.44	-0.20	-0.86	<0.001
ARCOS	≤50	160	2.687	0.507	0.78	4.22	19.07	-0.19	-0.85	<0.001
ARCOS	≤40	151	2.680	0.508	0.68	4.21	20.16	-0.16	-0.76	<0.001
BIRDLIFE	Full	57	15.582	0.215	0.44	4.25	17.71	0.01	0.05	<0.001
BIRDLIFE	≤60	57	15.582	0.215	0.44	4.25	17.71	0.01	0.05	<0.001
BIRDLIFE	≤50	57	15.582	0.215	0.44	4.25	17.71	0.01	0.05	<0.001
BIRDLIFE	≤40	56	15.901	0.201	0.41	4.08	17.20	0.01	0.02	<0.001
ICRAF	Full	264	6.433	0.339	0.54	6.11	28.21	-0.05	-0.24	<0.001
ICRAF	≤60	264	6.433	0.339	0.54	6.11	28.21	-0.05	-0.24	<0.001
ICRAF	≤50	264	6.433	0.339	0.54	6.11	28.21	-0.05	-0.24	<0.001
ICRAF	≤40	253	6.853	0.316	0.48	5.85	28.16	-0.06	-0.31	<0.001
RECOR	Full	35	5.455	0.411	0.71	5.91	24.96	0.08	0.34	<0.001
RECOR	≤60	34	6.220	0.367	0.64	4.04	18.13	-0.09	-0.41	<0.001
RECOR	≤50	34	6.220	0.367	0.64	4.04	18.13	-0.09	-0.41	<0.001
RECOR	≤40	34	6.220	0.367	0.64	4.04	18.13	-0.09	-0.41	<0.001
WAG	Full	269	3.577	0.565	0.74	12.98	34.52	-0.69	-1.84	<0.001
WAG	≤60	224	4.054	0.520	0.46	11.00	38.14	-0.29	-0.99	<0.001
WAG	≤50	196	4.126	0.498	0.46	8.74	34.71	-0.17	-0.67	<0.001
WAG	≤40	169	4.678	0.443	0.41	7.05	32.15	-0.13	-0.58	<0.001
WFZ	Full	419	3.800	0.533	0.60	6.89	28.26	-0.20	-0.84	<0.001
WFZ	≤60	415	3.892	0.525	0.55	6.73	28.10	-0.22	-0.92	<0.001
WFZ	≤50	411	3.969	0.518	0.53	6.62	27.95	-0.23	-0.96	<0.001
WFZ	≤40	383	4.169	0.496	0.52	5.85	26.25	-0.22	-0.98	<0.001

Table S4. Analysis of 25 FLR projects with estimates of project carbon, landscape baseline carbon, and forward projection of carbon. Project area is calculated in a GIS using project polygons shared with MSU. Baseline Carbon is the sum of all carbon measured from the VHR machine learning analysis within the project area polygons. 30-Year Projection1 (tC) is the estimated carbon sequestered in over a 30 year period within the project area polygons. 30-Year Projection2 (tC) is 80% of estimated carbon sequestered in over a 30 year period within the project area polygons to account for some loss.

Country	Project	Project Area (ha)	Baseline Carbon (tC)	30-Year Projection ¹ (tC)	30-Year Projection ² (tC)
Ghana	CERATH_GH	11.15	533.28	236.19	188.95
Ghana	GOSH_GH	769.00	31,905.20	15,772.80	12,618.24
Ghana	HERP_GH	167.37	7,999.98	2,042.35	1,633.88
Ghana	IGGS_GH	202.47	6,377.04	6,176.35	4,941.08
Ghana	INEC_GH	91.33	160.33	5,319.17	4,255.34
Ghana	PADO_GH	80.24	1,306.49	9,927.28	7,941.82
Ghana	SAFI_GH	214.85	2,155.42	7,433.12	5,946.49
Kenya	DNRC_KE	229.03	107.35	5,618.33	4,494.66
Kenya	DREK_KE	1	35.47	288.38	230.71
Kenya	EPZ_KE Samba	69.92	134.22	1,683.77	1,347.02
Kenya	EPZ_KE Turkana	80.92	62.02	1,718.19	1,374.55
Kenya	Fairtree_KE	2,395.18	8,952.52	26,975.10	21,580.10
Kenya	ILEG_KE	785.82	1,447.63	18,321.27	14,657.02
Kenya	ITF_KE	10.82	218.08	84.81	67.85
Kenya	KEV_KE	176.34	205.43	12,844.06	10,275.21
Kenya	KFT_KE	36.43	94.79	1,362.30	1,089.84
Kenya	MKEC_KE	19.49	64.22	522.87	418.29
Kenya	Sadhana_KE	16.74	10.34	408.06	326.45
Malawi	WAG_MW	64.00	185.29	2,054.71	1,643.77
Malawi	WfZ_MW	4,811.11	7,426.30	329,351.00	263,481.00
Rwanda	ARCOS_RW east	684.79	1,672.57	32,566.75	26,053.40
Rwanda	ARCOS_RW west	657.49	852.56	40,569.50	32,455.60
Rwanda	BIRDLIFE_RW	179.97	9,905.66	44,086.60	35,269.30
Rwanda	ICRAF_RW	1,001.31	621.81	29,417.36	23,533.89
Rwanda	RECOR_RW	100.23	73.63	4,938.07	2,539.64