

Sampling Methods and Carbon Flux Models for Spekboom
Restoration Projects:
Towards a Carbon Accounting Methodology

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1 Introduction

Developing a methodology for the carbon accounting of a restoration (revegetation) project requires a thorough assessment of the available published data on restoration protocols with the aim to either develop models of carbon flux over time (typically Tier 2 methods) since the start of the revegetation activity, or sampling methods for determining carbon flux over time. Here I provide sampling methods and summarize current available data for modeling carbon (as CO₂ equivalents) sequestered over time by planting spekboom (*Portulacaria afra*) truncheons within its native distribution range (habitat) (Vlok *et al.*, 2003). Revegetation with spekboom truncheons is most effective in an ecosystem where spekboom naturally occurs as a dominant species (referred to as spekboom thicket or spekboomveld - see Figure 1 and Appendix A for finer scale maps), but had been depleted through injudicious land management practice. In this context it is an effective ecological restoration strategy, that has been shown to sequester carbon while facilitating the regeneration of biodiversity on sites where naturally occurring spekboom have been eradicated (van der Vyver *et al.*, 2013). A biodiversity and habitat specialist should recommend a target site for revegetation along with a recommended planting density to eliminate any biodiversity impacts through the project activities. This work aims to inform a robust and relatively uncomplicated carbon accounting methodology to account for carbon sequestered through revegetation with spekboom truncheons, which should facilitate easy adoption by current and planned restoration initiatives within this ecosystem.

Restoration protocol

The current protocol for restoration of degraded and transformed terrain that was once spekboom-rich, is through the mass planting of spekboom cuttings or truncheons harvested from large mature plants. Studies on plots that have been planted in this way (i.e. with a monoculture of planted spekboom truncheons), suggests that the protocol facilitates increasing biodiversity regeneration along with increasing carbon sequestration over time (van der Vyver *et al.*, 2013). Truncheon harvesting protocols involves cutting truncheons from the topmost branches, and ensuring that not more than one third of the source plant is harvested in this way, to not deplete current source populations. It is also important to harvest truncheons from nearby the target revegetation site - or at least within the same watershed boundaries, to maintain current genetic diversity patterns. Harvest sites should be monitored before and after harvesting of truncheons and clearly mapped and monitored to demonstrate natural recovery of harvest populations.

Previous experiments and restoration trials used truncheons of various sizes, although the unofficial rule of thumb dictates truncheons with a stem diameter of 30 mm, or roughly 60-100 cm in length. Smaller truncheons are also used (10-15 mm stem diameter), but are generally slower to grow and establish, yet preliminary data show these truncheons can be just as effective if planted in higher densities, if not more effective over time. Planting depth is generally around 5-15 cm. The planting pattern most often utilised is that of a 2 m by 2 m grid, but a 1 m by 1 m grid has also been shown to be more effective for rapid growth and carbon sequestration (see Figure 5 and Table 3). Various planting experiments have been conducted experimenting with clumped plantings and other patterns, and there is potential to innovate these patterns to maximise restoration success. High mortality (> 60%) of planted truncheons have been recorded throughout previous restoration efforts (van der Vyver *et al.*, 2021a), suggesting that potential improvements are likely in planting protocols with increased practice and experimentation. Planting of nursery-grown seedlings in bags, hardened through exposure to full sun and limiting water addition have been shown to be more effective, but these incur higher



planting effort and costs.

Models and sampling methods

I present linear models based on the scantily available data on carbon flux in four different carbon pools of spekboom-revegetated stands of various ages, from which the values of adjacent degraded stands (proxies) is subtracted to model carbon sequestration potential over time. The available data used for developing the models presented here, both in terms of proxy (degraded state) and restoration stands of various ages, were obtained from only two sites namely Krompoort (Mills & Cowling, 2006) (first 27 years) and Rhinosterhoek (van der Vyver *et al.*, 2013) (35 to 50 years) for all pools considered here, namely aboveground biomass carbon (AGBC), litter carbon, soil organic carbon (SOC) and root carbon. Finer resolution models of AGBC sequestered over the first 5 years since planting (see Figure 5), is based on data obtained from the Thicket-wide Plot experiment (TWP) - the first results of which is partly published in van der Vyver *et al.* (2021b) and van der Vyver *et al.* (2021a). Although the TWP dataset includes sample data from stands across the spekboom thicket ecosystem, its first results only focus on aboveground biomass carbon. Therefore the core dataset from which the various models presented here to predict the first circa 30 years is based on data obtained from Krompoort (Mills & Cowling, 2006).

This scarcity of available data necessitates developing a methodology that requires a monitoring, research and verification (MRV) strategy where collection of field data and related site-specific modeling of sequestered carbon is a requirement (Tier 3 method), rather than a system reliant on pre-determined models for each pool based on data obtained from a single site. However it is preferable that a combination of these approaches be considered in a spekboom methodology, mainly due to the destructive nature of the soil and root sampling process. Since the sampling of root and soil carbon is recommended only every 5 years, the use of the models provided here may be used in combination with field sampling to account for the interim years between sampling periods. Adjustments will then need to be made accordingly once sampling results are obtained to account for actual gains and losses.

Target site selection

Spekboom-rich vegetation types are entwined with various other vegetation types mostly hostile to spekboom establishment across its range, and a high degree of patchiness in its distribution and that of its associated carbon pools are observed at a landscape scale. Successful revegetation with spekboom relies on favourable habitat conditions and thus the selection of a feasible target planting site with an imposed limit on browsing herbivores accessing planted stands for the first years since being planted (van der Vyver *et al.*, 2021b). Frost and exposure to herbivores during the first 5-10 years of planting are factors that negatively affect restoration success (Duker *et al.*, 2015b; Duker *et al.*, 2015a; van der Vyver *et al.*, 2021b). The former can be eliminated through the selection of an appropriate target site, while the latter may be kept in check through erecting fences or other barriers preventing herbivore access, particularly large antelope like Kudu (and Impala where they have been introduced) and domestic herbivores such as goats and cattle.

Baseline or reference level establishment

The relevant tool to identify the baseline scenario and demonstrate additionality in A/R CDM project activities are best suited to identify the baseline scenario of a target site for restoration. Accounting for carbon stock and flows requires the establishment of a baseline carbon stock value for all pools to be accounted for that locally define the degraded state and the continuing business-as-usual scenario in the absence of the proposed or established revegetation project. This baseline should ideally be



estimated from the proposed site targeted for revegetation, but may also be derived from a nearby degraded site that can serve as proxy of an already planted site. Such proxy sites need to be of similar slope, aspect and degradation status as that of the proposed targeted revegetation stand and not relatively close to the area planted. It is recommended to make an allowance for established spekboom restoration stands during the past 10 years that have not conducted any baseline estimates beforehand to become eligible as potential carbon projects, provided that the relevant data for this purpose is sourced from a stand that can be proven to characterize the state of the revegetated site before planting.

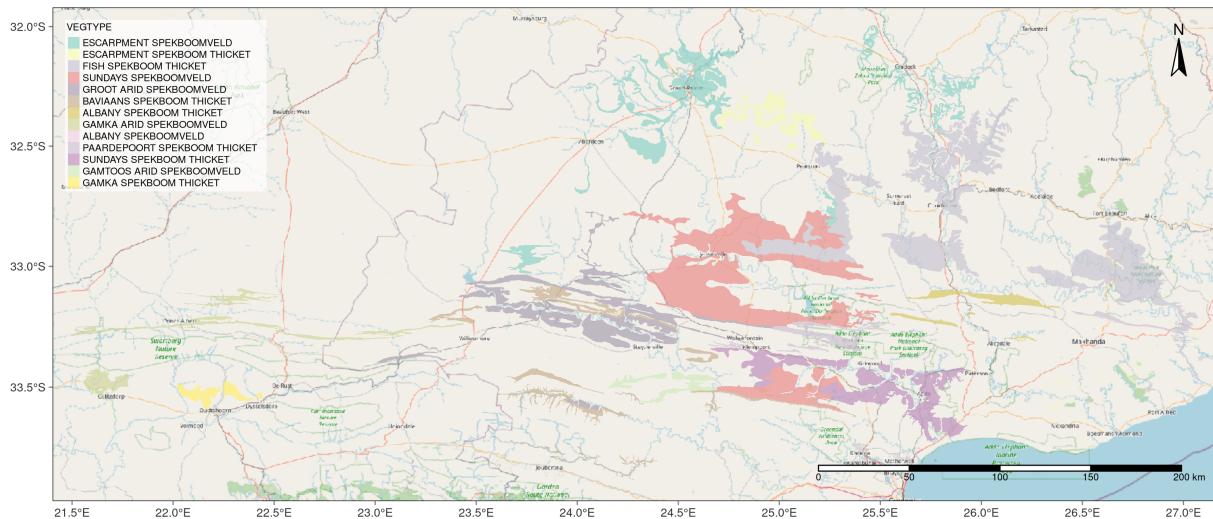


Figure 1: The regional-scale distribution of subtropical spekboom thicket habitat (Vlok et al. 2003), where spekboom naturally occurs as a canopy dominant species. Note that there is a large measure of variability in habitat even within this delineated area and landscape- or farm-scale habitat delineation of target planting areas are highly recommended.

The first steps towards establishing a baseline involves identifying a target planting area and mapping it in terms of its boundaries, slope, landform, aspect and existing vegetation cover on a landscape scale. Stratification of the target area is required and should at least be based on landform and existing vegetation cover, with other optional relevant parameters such as soil type, slope, elevation and aspect taken in consideration. This stratification of the target planting area is the basis on which the sampling design for baseline estimates and subsequent monitoring of carbon flows within each identified pool are to be built. During baseline estimation, which ideally should be conducted before planting starts, a thorough sampling of the standing carbon stock within each of the four carbon pools, namely aboveground standing biomass carbon (AGBC), litter carbon (LC), root carbon (RC) and soil organic carbon (SOC) is required. The methods provided here for estimating baseline values is similar to those employed for subsequent monitoring of carbon flux over time, with the exception that baseline estimation involves more intensive sampling effort to establish the appropriate number of sampling points to detect carbon stocks within defined confidence limits (uncertainty). The results obtained from the baseline estimation will inform the subsequent sampling strategy in terms of number of sampling points, to adequately quantify carbon flows over time and their associated uncertainty values.



In this study I focus on each of the four carbon pools eligible for accounting sequestered carbon over time, namely soil organic carbon (SOC), root, litter and aboveground standing biomass (AGBC). For each of these pools I present models of carbon sequestration over time by drawing from data available from published and peer-reviewed studies on carbon density on stands planted with spekboom truncheons in the past ((mills2006rate)). I also outline a proposed method for sampling carbon stock, both at baseline estimation and for subsequent sampling during the lifetime of a project, for each of the identified carbon pools.

Uncertainty

The purpose of an uncertainty assessment is to understand, quantify and document the causes of uncertainty in both individual estimates and overall totals derived from samples. "Uncertainty depends on the analyst's state of knowledge, which in turn depends on the quality and quantity of applicable data as well as knowledge of underlying processes and inference methods" (Ogle *et al.*, 2019).

When establishing baseline and subsequent monitoring protocols, uncertainties should be reduced as far as is practically possible. For all carbon estimations, all sources of uncertainty estimation should be made explicit and the method of used in quantification and modeling outlined during both the baseline assessment process and subsequent monitoring protocols. The four major sources of uncertainty that need to be accounted for during baseline assessment and subsequent monitoring of spekboom revegetation projects include, but is not necessarily limited to i) sampling uncertainty - i.e. uncertainty due to sample size and its probability of detecting a change above the background variability of sample results within a carbon pool, ii) model uncertainty relating to the quality of the specific allometric models or ratios used, iii) model uncertainty derived from ex-ante models of soil and root carbon sequestration used for estimating annual carbon sequestration within these pools within a five year cycle when a sampling event occurs, iv) uncertainty in accuracy of sampling procedures, and v) uncertainty inherent in laboratory methods for estimates of carbon content (in soil or biomass).



To minimize sampling uncertainty, the A/R Methodological Tool for the calculation of the number of sample plots for measurements within A/R CDM project activities facilitates the selection of number of field sample plots, based on the size of an individual sample, the area of the stratum being sampled and the target precision (acceptable margin of error) required. The 90% confidence level is considered an acceptable margin of error by the Methodological tool for estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities and may be applied for root and SOC estimates also. The same tool also provides discount factors based on the uncertainty calculation:

$$U = \pm \left(\frac{1.692 \cdot \sigma}{\mu} \right) \cdot 100\% \quad (1)$$

Any estimates of biomass or carbon from allometric models, including root:shoot ratios, need to be included in uncertainty assessments. Here also, the applicable CDM tool for demonstrating appropriateness of allometric equations for estimation of aboveground tree biomass in A/R CDM project activities is useful to minimize uncertainty and should be followed when using an allometric equation for estimation of baseline and project aboveground biomass, respectively. Details on the allometric models available for spekboom-rich habitats is given under the aboveground biomass carbon section below.

The outputs of an uncertainty assessment process provide both accuracy and precision of estimates for every carbon pool value expressed as its associated uncertainty. An uncertainty discount should be applied according to the table provided in the Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities tool, provided below (see Table 1).

Compound uncertainties need to be calculated for total biomass estimates using the equations provided by Ogle *et al.* (2019), Chapter 3. This also includes compound uncertainties from various allometric models used in estimating tree or shrub biomass and carbon.

Here the appropriate equation for estimating combined uncertainty by addition or subtraction is given as:

$$U_{total} = \frac{\sqrt{(U_1 \cdot x_1)^2 + \dots + (U_i \cdot x_i)^2 + \dots + (U_n \cdot x_n)^2}}{|x_1 + \dots + x_i + \dots + x_n|} \quad (2)$$

Where: U_{total} = the percentage uncertainty in the sum of quantiles (half the 95% confidence interval divided by the total (i.e. mean) and expressed as a percentage

x_i = quantities to be combined; x_i may be a positive or negative number

U_i = the percentage uncertainties associated with each of the quantities

For multiplication of estimated values, the compound uncertainty can be calculated as:

$$U_{total} = \sqrt{U_1^2 + \dots + U_i^2 + \dots + U_n^2} \quad (3)$$

Where: U_{total} = the percentage uncertainty in the sum of quantiles (half the 95% confidence interval



divided by the total (i.e. mean) and expressed as a percentage

U_i = the percentage uncertainties associated with each of the quantities

To maintain conservative mean estimates in the face of uncertainty, discounts are applied to the yield values, either individually or the compounded estimates according to Table 1 below.

Table 1: Uncertainty discounts applicable to estimates of annual carbon yields across all pools.

Uncertainty	Discount (% of U)
$U \geq 10\%$	0%
$10 < U \leq 15$	25%
$15 < U \leq 20$	50%
$20 < U \leq 30$	75%
$U > 30$	100%

2 Belowground Carbon Pools

The need for a combination of model-derived annual sequestration values for root and soil carbon pools, due to the destructive nature of sampling is recommended here. A combination of field sampling and existing models may be feasible to aid with the financial viability of potential projects. Annual sampling of aboveground biomass carbon (AGBC) is recommended, while soil organic carbon and root carbon should be sampled a minimum of every 5 years. This is to limit the destructive nature of sampling these two carbon pools and their relatively slower accumulation rates. Since there is much die-off of planted truncheons within the first year, it is recommended to assess the first round of carbon sequestered at least one, or preferably two full years after planting.

Both soil and organic carbon sampling can be combined through a single effort of sampling successive soil layers of a predetermined depth with three or more adjacent samples as cubes extracted from each layer.

The projections below should give some guidance on potential sequestration rates based on actual data from revegetated stands over various time intervals.

2.1 Soil Organic Carbon (SOC)

2.1.1 SOC sampling

The tool for estimation of change in soil organic carbon stocks due to the implementation of A/R CDM project activities provides guidance on SOC sampling and analysis procedures. An approved Excel spreadsheet is used for some calculations.

Soil organic carbon estimation methodology involves three main components:

- i)* The sampling design established at baseline estimation and,
- ii)* the sampling process repeated with each soil depth layer, and
- iii)* the required values obtained from a sample through post-sample processing and subsequent laboratory analysis.

The sampling design needs to be able to detect significant change in carbon stock over time and account for uncertainty. A stratified random sampling approach is recommended, and to be established



at baseline estimation before the revegetation or any restoration action commence, or by sampling an adjacent area to an already planted stand proven to be of the same characteristics of soil type, slope, aspect and degradation status. The tool for calculation of the number of sample plots for measurements within A/R CDM project activities is useful in this regard. Some studies and similar methods on optimised sampling are available (De Gruijter *et al.*, 2015; Gruijter *et al.*, 2018; Gruijter *et al.*, 2019), for example a method and associated software (replicated in the R packages ospats and SamplingStrata) for determining an efficient sampling design based on predictions and quantifying uncertainty using the same strategy as the applicable tool, but factors in cost-efficiency. Stratification should be explicitly mapped within the target planting area, and be based on known variables that affect variation on soil SOC, such as position in the landscape (eg. footslope, midslope, crest), soil type, vegetation type and aspect. Other stratification variables can also be derived from remote sensing data.

In the absence of any available fine-scale data of soil organic carbon or a digital SOC map at a landscape (or farm) scale, a grid sampling approach is initially required for each stratified unit, in order to capture variation in SOC at a relevant local scale and determine measures of uncertainty. Each stratification unit should have at least 5-20 sample points, depending on size. Ideally, each of the sample points should consist of at least 4-10 separate sample points, each spaced by about 1 meter to capture local variability. The general aim of this approach is to capture a representative range of variation within a stratified unit, both on a stand level and at a landscape scale. Since this procedure implies high sampling effort and costs, depending on target area identified, the procedure outlined by Gruijter *et al.* (2018) is recommended to provide the best stratification map and the number of required samples to detect significant change over time and based on the costs of sampling, uncertainty and prediction error.

Sampling of individual soil layers requires a decision on the total estimated soil depth for which SOC is accounted for on a project level, and the depth of each soil layer sampled. Some estimates of potential gain from different sampling depths are presented as Figure 2 and Table 2. The depth of each individual sample layer may be selected based on site characteristics or project sampling preference. The number of soil depth layers determine the number of samples needed for separate laboratory analysis and thus affects sampling costs. It is recommended that the minimum total soil depth layer be 10 cm - which can extend to a maximum of 1 m deep and beyond. Aiming to go deeper is often limited on shallower soils (usually at depths > 50 cm) where bedrock is close to the surface, but on deeper soil has the added advantage of accounting for longer-term (35+ years) carbon accumulation there. Typically, sample soil layer depth is often set at between 10-20 cm per layer, where each layer is excavated as two or three adjacent 10 cm × 10 cm cubes preferably using chisels and spoons, successively up to the chosen total soil depth. It is recommended that at least two soil depth layers should be sampled at each sampling point. Should a soil probe (instead of an excavated 10 cm by 10 cm cube) be used for this purpose instead, it is important to note that its use introduces bias to bulk density and eventually soil SOC estimates due to compaction of the surface layer of soil in relation to the diameter of the probe, as reported by Sharma *et al.* (2020). Thus, if using a soil sampling probe for the sampling of individual soil layers, it is important to follow the equivalent soil mass (ESM) method (Sharma *et al.*, 2020) instead of calculating SOC stock via a biased bulk density value.

Prior to the excavation of soil pits, all leaf litter and live plant material are to be removed from the soil surface. At baseline estimation and after 10-12 years of project development, this top layer of litter



may be taken as a litter sample (see litter carbon sampling method below). Cubes of soil ($10\text{ cm} \times 10\text{ cm} \times$ soil layer depth) should be carefully excavated out of each layer. Each sample point should take samples of two (or three) adjacent $10\text{ cm} \times 10\text{ cm}$ soil cubes, separated by not more than 20 cm (but preferably next to one another) and be bagged. One of these samples will be used to determine soil bulk density, rock volume and root biomass, the other will be sent to the lab for determining SOC concentration at that depth level. Fine-scale variation of different soil depth layers is generally not necessary, provided that both the samples sent for lab analysis and for bulk density determination are adequately mixed across the depth of the sample profile.

The estimation of carbon within a sample requires the analysis of organic C concentration (ISO 10694, 1995 or ISO 14235, 1998), bulk density (ISO 11272, 1998), the content of fine and coarse particles (and associated OC and N) (ISO 11277, 2009), and soil depth (ISO 25177, 2008). At larger scales (e.g., landscape, regional, national), high-throughput techniques such as infrared spectroscopic methods may be used to quantify SOC in large soil sample sets (ISO 17184:2014) (Bispo *et al.*, 2017).

$$C_{stock} = \sum_{i=1}^n 10 \cdot p_i \cdot SOC_i \cdot BD_i \cdot (1 - CP_i) \quad (4)$$

where: C_{stock} (in kg.m^2) is the carbon stock value p_i (in m) is the thickness of the soil layer i

SOC_i (in g.kg^{-1}) is the organic carbon concentration of layer i in fine soil

BD_i (in kg.dm^{-3}) is the bulk density of layer i of fine soil

CP_i is the percentage of coarse particles of layer i

n is the number of soil layers.

Samples sent for lab analysis should be air-dried, and sieved to separate $<2\text{ mm}$ fraction of the soil and analysed for organic carbon using either the Walkley–Black method Walkley (1947), or other standard laboratory methods with published evidence of its efficacy.

The separate samples (of the same dimensions) from each layer to calculate bulk density and rock volume should be dried in an oven at 60°C until constant mass, weighed and then wet-sieved to obtain the fine grained soil component ($<2\text{ mm}$). The volume of the residual rock and coarser fragments should be determined by water displacement in a measuring cylinder. It is necessary to calculate SOC in relation to bulk density as recommended by Poeplau *et al.* (2017), who showed a systematic overestimation in most soil SOC calculations.

The above method is the standard that has been applied to most estimations of SOC in the past, yet Poeplau *et al.* (2017) showed a strong bias in many estimates due to the accounting of the coarse soil fraction when determining soil bulk density. We provide both methods here, but recommend the latter presented below and according to which our annual projected soil carbon yield model has been determined (see Table Table 2). With this method, care must be taken to account for the coarse soil fraction (volume of stones and gravel $> 2\text{mm}$ in diameter) in both equations for calculating the bulk density of fine soil (Equation 5 below) and the volume of the fine soil (Equation 6 below).

$$BD_{fineSoil} = \frac{mass_{sample} - mass_{stones}}{volume_{sample} - \frac{mass_{stones}}{\rho_{stones}}} \quad (5)$$



where:

$BD_{fineSoil}$ = Bulk density of fine soil < 2mm in diameter

$mass_{sample}$ = mass of the sample

$mass_{stones}$ = mass of the coarse soil fraction

$volume_{sample}$ = volume of the total sample

ρ_{stones} = Density of stones (approximation at 2.6 g. cm³)

$$SOCstock_i = SOCcon_{fineSoil} \cdot BD_{sample} \cdot depth_i \cdot (1 - stoneFraction) \quad (6)$$

where:

$SOCstock$ = Soil Organic Carbon stock

$SOCcon_{fineSoil}$ = SOC content in fine soil (%)

BD_{sample} = Bulk density of the sample

$depth_i$ = depth of the respective soil layer

The above two equations can be simplified by completely disregarding soil bulk density as a property to be sampled, as for the calculation of SOC stocks alone it is not needed. Therefore these equations can be reformulated as follows:

$$FSS_i = \frac{mass_{fineSoil}}{Volume_{sample}} \cdot FSS_i \quad (7)$$

and

$$SOCstock_i = SOCcon_{fineSoil} \cdot FSS_i \quad (8)$$

where:

FSS = fine soil stock

Should this method be followed it has implications for sample preparation in that in the first case, for estimating $BD_{fineSoil}$ the volume of coarse fragments has to be estimated by weighing stones and coarse roots separately, while FSS_i would only need the total mass of the fine soil contained in the known volume of sample. For root biomass estimation the root fraction of the sample will however need to be dried and weighed. This greatly simplifies SOC calculation when using the probe method as all coarse fragments can be discarded.



2.1.2 Annual SOC Yield Model

The annual SOC yield model used data from Mills and Cowling (2006) for each layer sampled, including that of the degraded stand that is here defined as the reference or baseline. The SOC values of the reference stand was subtracted for each of the corresponding layers of soil samples for each of the restoration stands of various ages to obtain yield. Yield was modelled over time (in years) and the initial models showed a high yield of > 20 tCO₂e during the first year after planting for all soil layers. This was deemed unrealistic and likely a result of the high variation of SOC at stand level and the paucity of sample data. This initial yield value was then subtracted throughout the successive years, resulting in the values presented in Table 2.

Figure 2 show the annual tCO₂e yield models derived from soil sample data provided by (Mills & Cowling, 2006) based on three different sampling depths.

2.2 Root Carbon

2.2.1 Root Carbon Sampling

The root carbon pool forms part of the belowground carbon fraction in an ecosystem. There are two main aspects of sampling for root carbon, namely the sampling design and the actual extraction and processing of the sample to arrive at an estimate of root carbon for each stratified unit. Since no root:shoot ratios for neither spekboom nor for most other vegetation in the ecosystem exist, there is a need to sample root carbon directly. This procedure can be included in the soil organic carbon sampling process outlined above, and follow the same sampling design where from each of the soil layer samples root biomass can be extracted by wet sieving from the same samples used for determining bulk density. Due to the destructive nature of this sampling method it is recommended that as with the soil organic carbon, sampling for root carbon starts with baseline or reference level stock assessments, and thereafter is repeated once every 5 years as with soil carbon.

The extracted roots should be dried in an oven at 60° C until it achieves a constant mass, whereafter the standard biomass to carbon fraction can be applied to the dry root biomass.

$$C = BM \cdot CF \quad (9)$$

where:

CF (Carbon fraction) = 0.47

BM = Biomass

The mass of roots per volume (stones included) should be determined for each depth layer. Since there is some existing data available on root carbon sequestration (although only at one site, namely Krompoort) (Mills & Cowling, 2006), there exists a possibility to determine annual sequestration according to this model (see the root carbon projection below) and issue annual credits accordingly. Adjustments can then be made according to the actual sequestration every five year interval, either through subtraction of that year's credits - should the measured carbon sequestration over each five-year interval fall short of the actual modelled sequestration, or through the addition of more credits



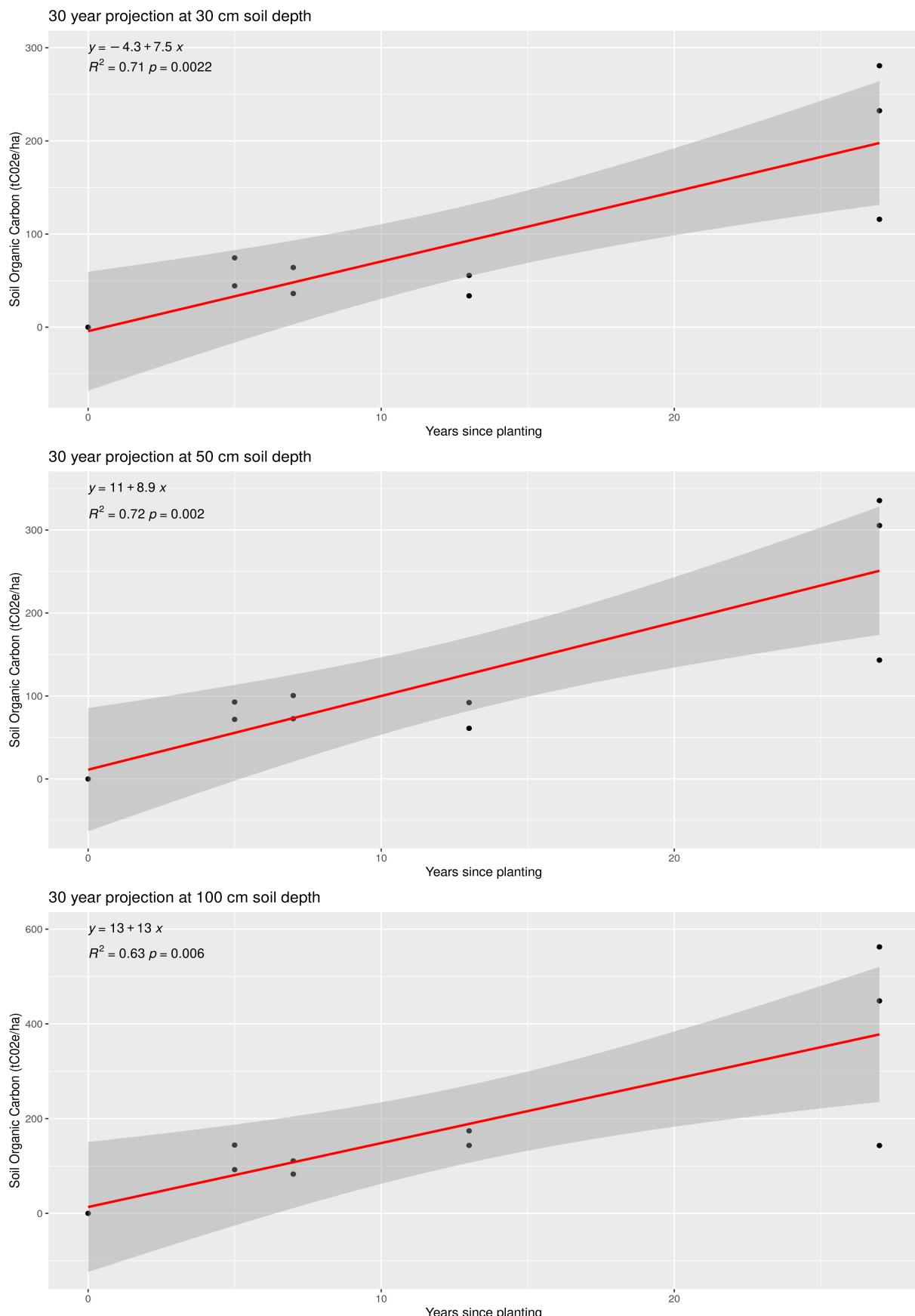


Figure 2: Linear models of SOC yield in tCO₂e per annum since planting according to three sampling depths: 0-30 cm, 0-50 cm and 0-100 cm



where the sequestration was measured higher than the first five-year interval.

The stock-difference generic method proposed by Ogle *et al.* (2019) (Equation 2.5) can be used to determine carbon stock change in the root carbon pool, as with the other carbon pools, by the following equation:

$$\Delta C = \frac{(C_{t_2} - C_{t_1})}{(t_2 - t_1)} \quad (10)$$

Where: ΔC = Annual carbon stock change in the pool, tonnes C yr⁻¹

C_{t_1} = carbon stock in the pool at time t_1 , tonnes C

C_{t_2} = carbon stock in the pool at time t_2 , tonnes C

2.2.2 Annual Root Carbon Yield Model

Models for root carbon sequestration was developed with the same sample dataset provided by Mills and Cowling (2006) in the same method outlined under soil. Figure 3 show each of the root yield models according to total sampling depth.

2.3 Annual Belowground Carbon Yield Projection

Since the model uncertainty of the annual yield estimation for both root and soil carbon within the different layers was relatively high, after applying the appropriate discount factor (see Table Table 1), the estimated yield

3 Aboveground Carbon Pools

3.1 Aboveground Biomass Carbon

3.1.1 AGBC Sampling

Biomass sampling involves two main components: i) The sampling design, and ii) the method of carbon estimation within a sample

The method for sampling aboveground biomass C should account for the biomass that is already present in the reference condition or baseline, the biomass of planted spekboom as it grows over time and the biomass of regenerated vegetation that emerges spontaneously due to the new altered micro-environment created through the revegetation action over time. The mortality of planted truncheons can average around 70% after 1-2 years since planting date, and thus sampling should only be conducted after a year or two after revegetation occurred.

Here the sampling design should also be based on the stratification of the target area, as outlined above. The use of the A/R Methodological Tool for the calculation of the number of sample plots for measurements within A/R CDM project activities is sufficient to calculate the number of sample plots within a stratified unit. The tool requires some initial measure of variation within the stratum to be sampled. Here an initial sample of five plots, either circular (diameter of 5.7 m) or square (5 m



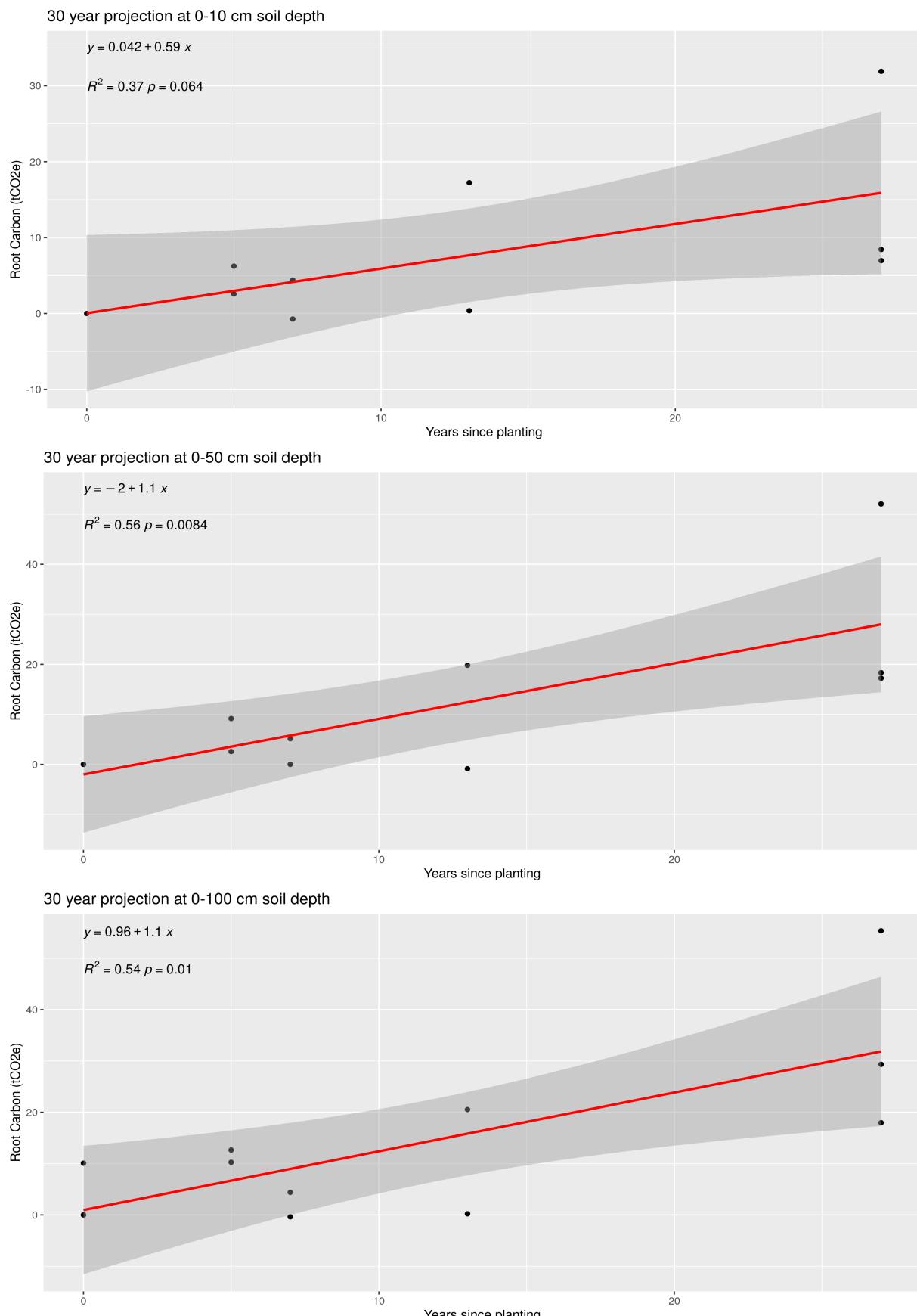


Figure 3: Linear models of root yield in tCO₂e per annum since planting according to three sampling depths: 0-10 cm, 0-50 cm and 0-100 cm



Table 2: Annual belowground biomass projections in $\text{tCO}_2\text{e.ha}^{-1}$ from the various models outlined above after uncertainty discount is applied.

Age	Soil 30cm	Soil 50cm	Soil 100cm	Root 10cm	Root 50cm	Root 100cm
0	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.86	0.00	0.00	0.00	0.00	0.01
4	8.35	8.24	9.08	0.00	0.87	1.28
5	15.83	17.12	22.57	0.27	2.01	2.55
6	23.31	25.99	36.07	0.85	3.14	3.82
7	30.79	34.87	49.57	1.44	4.28	5.09
8	38.28	43.75	63.07	2.03	5.42	6.36
9	45.76	52.62	76.56	2.62	6.56	7.63
10	53.24	61.50	90.06	3.20	7.70	8.90
11	60.72	70.38	103.56	3.79	8.84	10.17
12	68.21	79.25	117.06	4.38	9.98	11.44
13	75.69	88.13	130.55	4.97	11.12	12.71
14	83.17	97.00	144.05	5.55	12.26	13.98
15	90.65	105.88	157.55	6.14	13.39	15.25
16	98.14	114.76	171.05	6.73	14.53	16.52
17	105.62	123.63	184.54	7.31	15.67	17.79
18	113.10	132.51	198.04	7.90	16.81	19.06
19	120.58	141.38	211.54	8.49	17.95	20.33
20	128.07	150.26	225.04	9.08	19.09	21.60
21	135.55	159.14	238.53	9.66	20.23	22.87
22	143.03	168.01	252.03	10.25	21.37	24.13
23	150.51	176.89	265.53	10.84	22.51	25.40
24	158.00	185.76	279.03	11.43	23.65	26.67
25	165.48	194.64	292.52	12.01	24.78	27.94
26	172.96	203.52	306.02	12.60	25.92	29.21
27	180.44	212.39	319.52	13.19	27.06	30.48
28	187.93	221.27	333.02	13.78	28.20	31.75
29	195.41	230.14	346.51	14.36	29.34	33.02

- * Soil up to 30cm depth
- * Soil up to 50cm depth
- Soil up to 100cm depth
- † Root up to 10cm depth
- ‡ Root up to 50cm depth
- § Root up to 100cm depth



$\times 5\text{ m}$) in design with an area size of approximately 25 m^2 are required to be placed randomly within each stratum.

The methods for estimating tree (or/and shrub) biomass outlined in the A/R Methodological tool for estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities are applicable, especially those outlined under section 8.1.1 (Stratified random sampling), namely equations 12-17. All woody aboveground biomass should be sampled through the use of available species-specific allometric equations. For species where no allometric models are available, the use of allometric models for species of similar structure and stem density than those for which specific models are not available may be employed (surrogate tree species). Allometric models for spekboom and other species are provided by van der Vyver and Cowling (2019).

Generally, the allometric models require the input of plant species name, crown diameter and height, measured from the ground level to the highest point of the plant. Models that exclusively measure crown diameter may also be used provided their coefficient of determination (r^2) is equal to or more than 0.75. Larger plot size per stratum and the use of Unmanned Aerial Vehicles (UAV) with high resolution image sensors may be employed if it can be shown that measurements of plants through such image data correlate with measurements in the field and thus sufficient for feeding into the applicable allometric models.

Uncertainty

The applicable CDM tool for demonstrating appropriateness of allometric equations for estimation of aboveground tree biomass in A/R CDM project activities outlines requirements for allometric model selection and validity for use within the methodology.

6. A species-specific or group-of-species-specific allometric equation derived from trees growing in edapho-climatic conditions similar to those in the project area is considered appropriate, and hence can be used for ex post estimation of tree biomass, if at least one of the following conditions is satisfied

- (a) The equation is used in the national forest inventory, or the national GHG inventory, of the host Party;*
- (b) The equation has been used in commercial forestry sector of the host Party for ten years or more;*
- (c) The equation was derived from a data set of at least 30 sample trees, and the value of coefficient of determination (R^2) obtained was not less than 0.85.*

7. An allometric equation that does not meet the criteria listed under paragraph 6 above can be used for ex post estimation of aboveground tree biomass only if its appropriateness is demonstrated on the basis of field data obtained from sample trees as described in paragraphs 8 to 19 below.

Appendix B below provides available allometric models for quantifying biomass and carbon. The species list is by no means comprehensive and in some studies these models are applied to species of similar structure and size as those for which these allometric models were developed. According to criteria 6(c) above, only the models pertaining to spekboom (*Portulacaria afra*) qualify as a valid allometric model, as each of them are based on a sample size of 42, and all coefficients of determination (R^2 - values) amount to 0.85 and above. The other species-specific models provided vary in terms



of accuracy (as per R^2 value) and sample size, but none reach the 30 sample size requirement as per the above specification. Yet, paragraphs 8-19 in the tool provide guidance on which of these models and the data it is based on could be usable to determine carbon of other species within the baseline scenario, as well quantifying regeneration and growth of other species in subsequent monitoring. It also provides guidance on developing models from plants harvested from a potential site. Note that in Appendix B the allometric models with the smallest sample sizes ($n < 10$) are generally restricted to low biomass shrubs and dwarf shrub species.

Uncertainty pertaining to allometric models of tree and shrub species from plot data need to be made explicit. Uncertainties from carbon estimates using allometric models for both the baseline and subsequent monitoring need to be quantified using the same equations and protocols as outlined above.

3.1.2 Annual AGBC Yield Models

Projections from models based on carbon sequestration over time were developed from available data on aboveground biomass carbon from initial studies of stands planted with spekboom over a longer time period (5-50 years) (Mills & Cowling, 2006; van der Vyver *et al.*, 2013) and data from the thicket-wide plot experiment for the first 2-5 years after planting (van der Vyver *et al.*, 2021a, 2021b) are presented here.

The pattern in which truncheons were planted had a strong influence on Carbon sequestration over the shorter time period. A distinction is made between truncheon spacing over the target area, namely 1 m spacing vs 2 m spacing, but also between truncheon size.

3.2 Litter Carbon

Should litter be also accounted for, a baseline estimate needs to be established before the revegetation project starts (in the case of new projects) or with the help of a suitable proxy area (in the case of already established revegetated stands). The appropriate tool for estimation of carbon stocks and change in carbon stocks in dead wood and litter in A/R CDM project activities should be used for guidance.

After establishing a baseline or reference value, the sampling of litter and dead biomass is likely only feasible after a decade since planting activities started. The 30 year model (See Figure 6) shows an annual increment of $0.33 \text{ tCO}_2\text{e.ha}^{-1}$, starting from the fifth year after planting.

The same procedure of sample site selection (random stratified sampling) should be used with the litter carbon pools as with the other sites. Since the smaller sample frame will likely introduce more uncertainty, it is necessary to include more sample points within a stratified unit. The

The sampling of litter and dead biomass is likely only feasible after a decade after planting activities started. Although the litter component of aboveground carbon can be sampled by collecting all litter in a $25 \times 25 \text{ cm}$ frame at seven localities in each of the stands, and then drying samples in an oven at 60°C until constant mass. The same equation (equation 2 above) can be used to convert from biomass values to carbon. Care should be taken to separate all organic litter material from soil particles before weighing to determine mass.



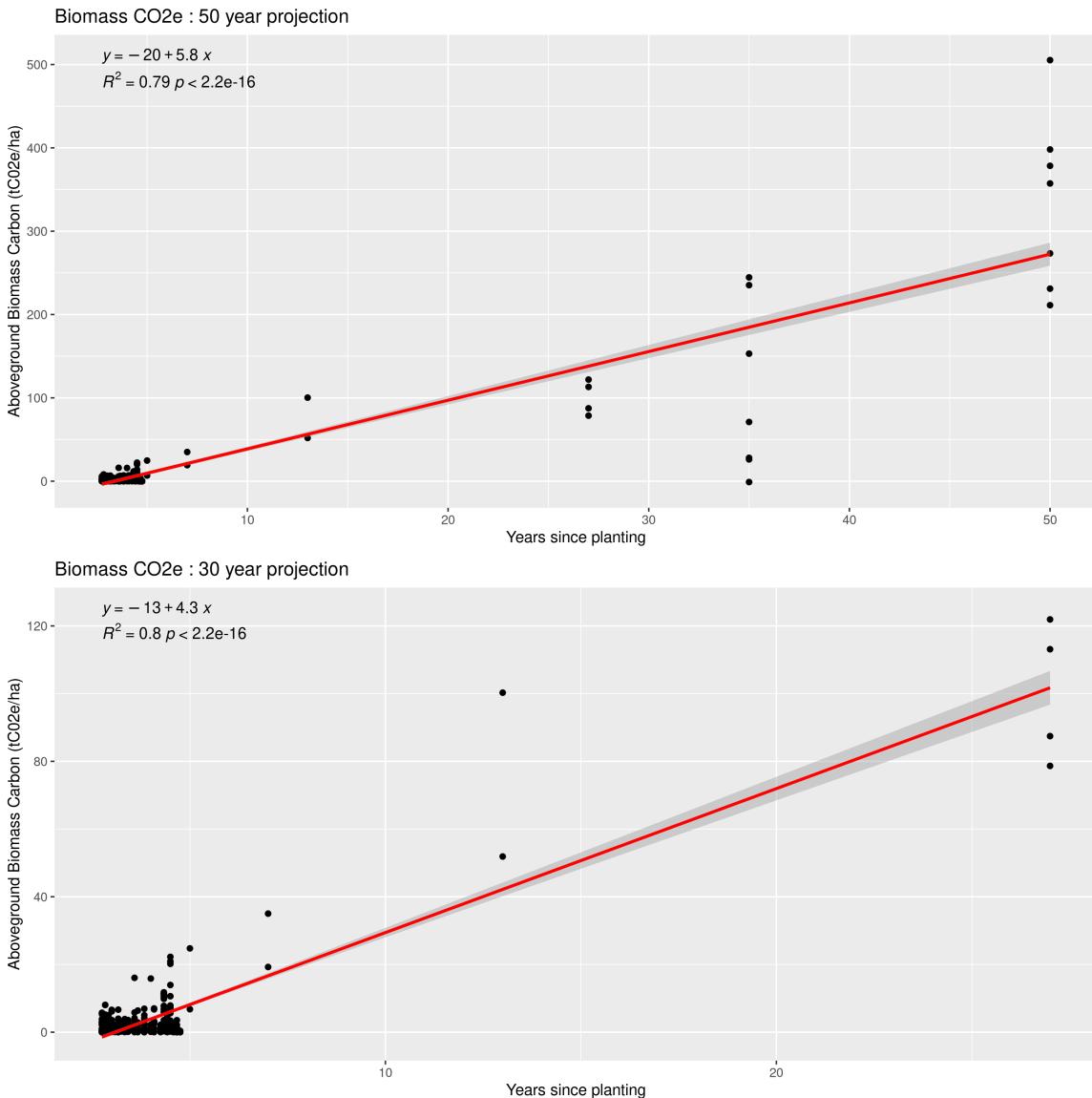


Figure 4: Model projections of aboveground biomass for both 30 and 50 year projections based on data from Mills and Cowling (2006) and van der Vyver et al. (2013)



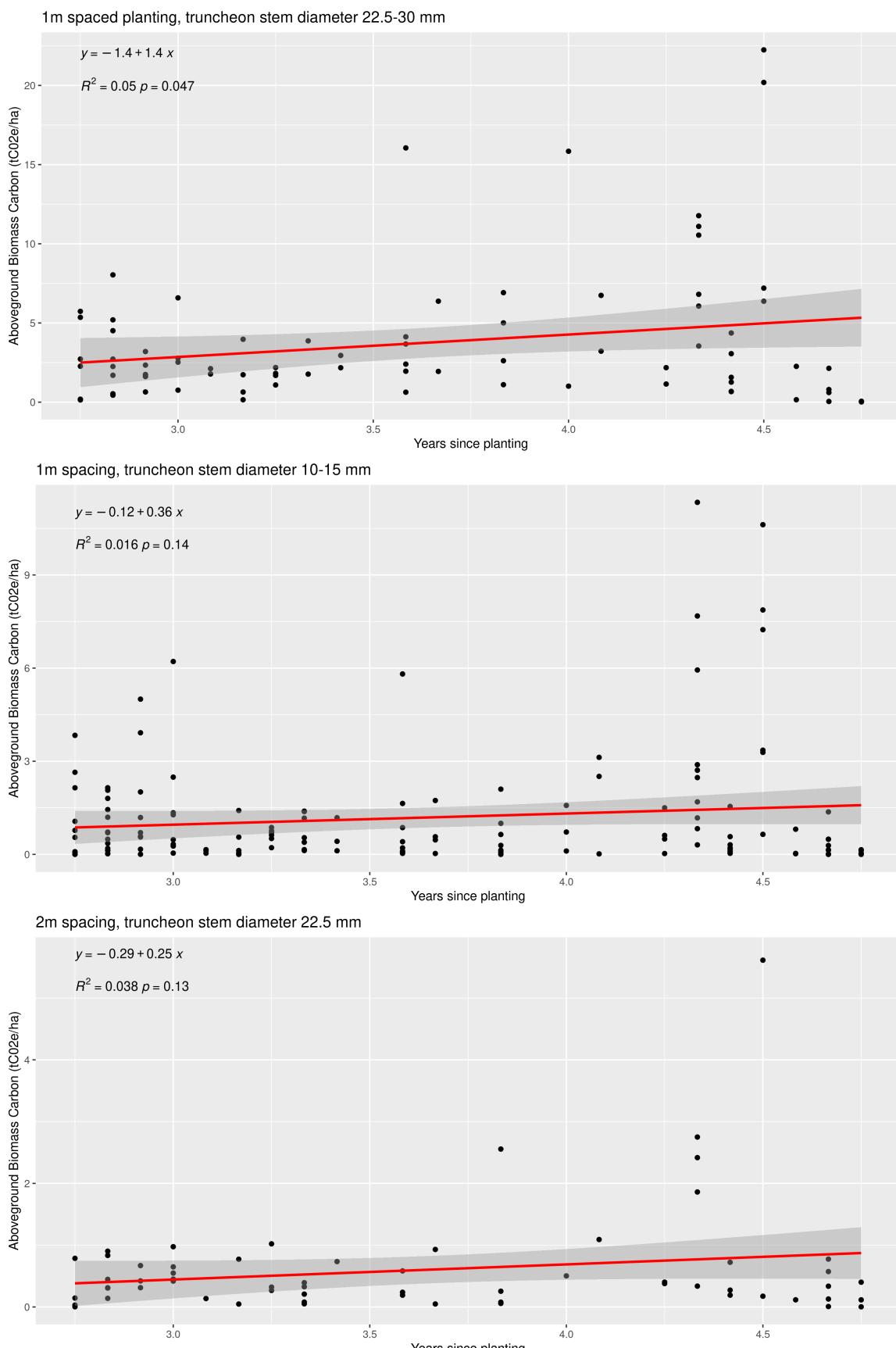


Figure 5: Model projections of aboveground biomass for the first 2-5 years from data derived from a biome-wide experiment (van der Vyver et al. 2021a, 2021b).



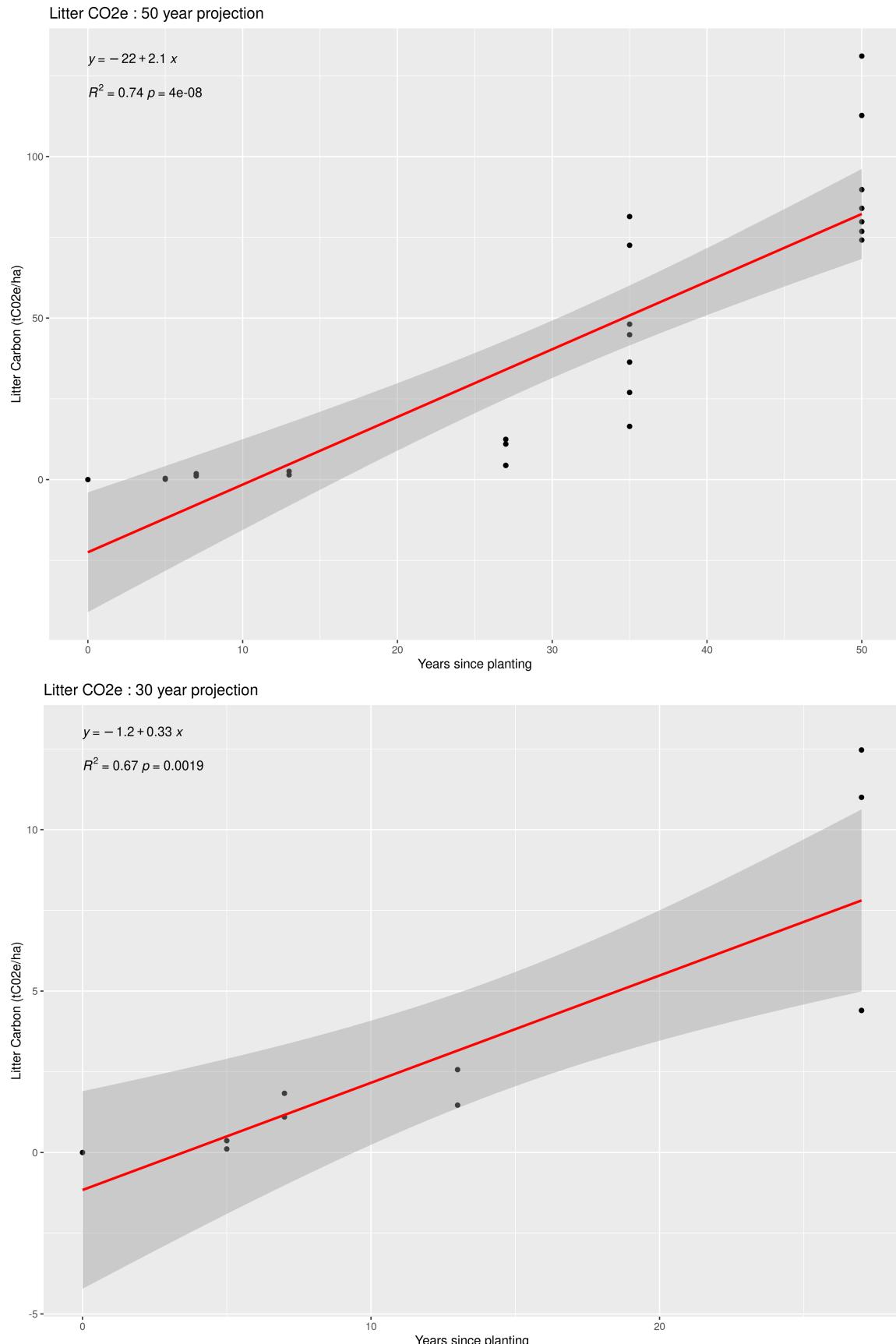


Figure 6: Model projection of Litter CO₂ from available data



3.3 Annual Aboveground Carbon Yield Projection

Table 3 below outlines potential aboveground carbon yield values based on data from available restoration plots and planting patterns. Note these yield values are not to be used for annual issuance of carbon credits, but should be sampled independently each year according to the relevant protocols outlined above.



Table 3: Annual aboveground biomass projections in $\text{tCO}_2\text{e.ha}^{-1}$ from the various models outlined above.

Age	Biomass30y*	Biomass50y*	Litter30y•	Litter50y⊕	Planting1▷	Planting2◁	Planting3▽
1	0.00	0.00	0.00	0.00	0.02	0.00	0.24
2	0.00	0.00	0.00	0.00	1.44	0.20	0.60
3	0.00	0.00	0.00	0.00	2.85	0.44	0.96
4	0.00	3.71	0.00	0.00	4.27	0.69	1.31
5	8.14	9.55	0.17	0.00	5.69	0.93	1.67
6	12.40	15.39	0.52	0.00	7.10	1.18	2.03
7	16.65	21.23	0.87	0.00	8.52	1.42	2.39
8	20.90	27.07	1.22	0.00	9.93	1.67	2.75
9	25.16	32.91	1.57	0.00	11.35	1.91	3.11
10	29.41	38.75	1.93	0.00	12.77	2.16	3.47
11	33.67	44.59	2.28	0.00	14.18	2.40	3.82
12	37.92	50.43	2.63	0.00	15.60	2.65	4.18
13	42.17	56.27	2.98	1.58	17.01	2.89	4.54
14	46.43	62.11	3.34	3.80	18.43	3.14	4.90
15	50.68	67.95	3.69	6.01	19.85	3.38	5.26
16	54.93	73.79	4.04	8.23	21.26	3.63	5.62
17	59.19	79.63	4.39	10.44	22.68	3.87	5.98
18	63.44	85.47	4.75	12.66	24.09	4.12	6.33
19	67.70	91.31	5.10	14.87	25.51	4.36	6.69
20	71.95	97.15	5.45	17.09	26.93	4.61	7.05
21	76.20	102.99	5.80	19.30	28.34	4.85	7.41
22	80.46	108.83	6.16	21.52	29.76	5.10	7.77
23	84.71	114.67	6.51	23.73	31.18	5.34	8.13
24	88.96	120.51	6.86	25.95	32.59	5.59	8.48
25	93.22	126.35	7.21	28.16	34.01	5.83	8.84
26	97.47	132.19	7.57	30.38	35.42	6.08	9.20
27	101.72	138.03	7.92	32.59	36.84	6.32	9.56
28	105.98	143.87	8.27	34.81	38.26	6.57	9.92
29	110.23	149.71	8.62	37.02	39.67	6.81	10.28
30	114.49	155.55	8.98	39.24	41.09	7.06	10.64

* Biomass 30 year model

* Biomass 50 year model

• Litter 30 year model

⊕ Litter 50 year model

▷ Biomass planting pattern: 1-1.2m long, stem diameter 22-30mm, spaced 1m apart

◁ Biomass planting pattern: 1 m long, stem diameter 22.5mm, spaced 2m apart

▽ Biomass planting pattern: 40 cm long, stem diameter 10-15mm, spaced 1m apart



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4 APPENDIX A - Distribution Maps of Spekboom Thicket Habitat

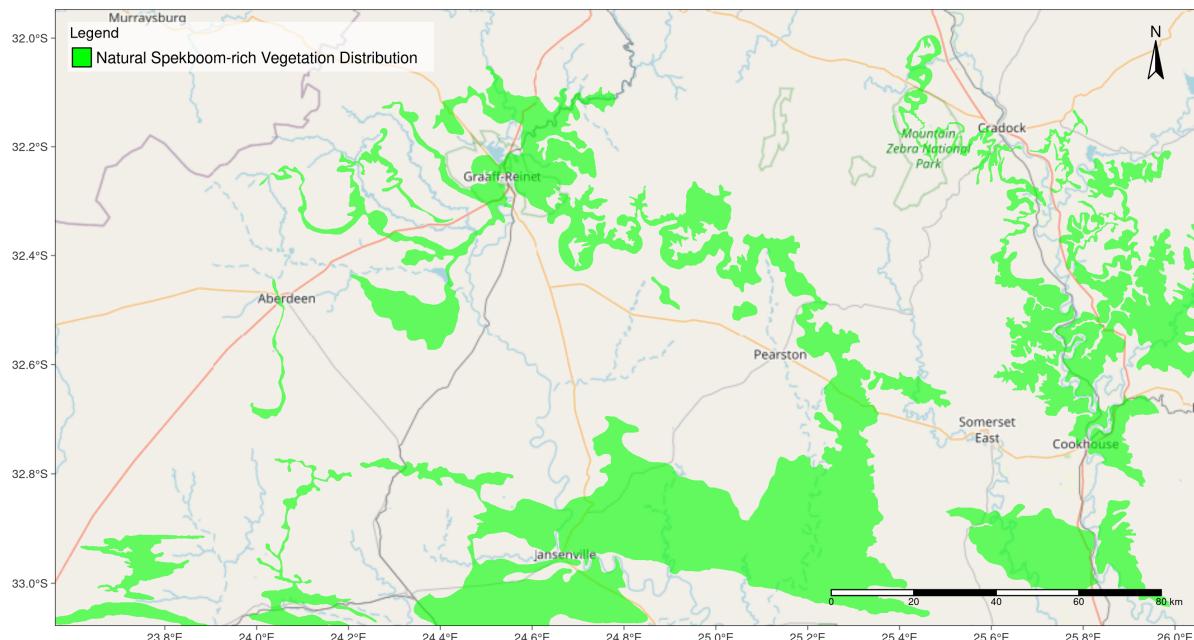


Figure 7: Map of Escarpment Spekboomveld and Escarpment Spekboom Thicket.

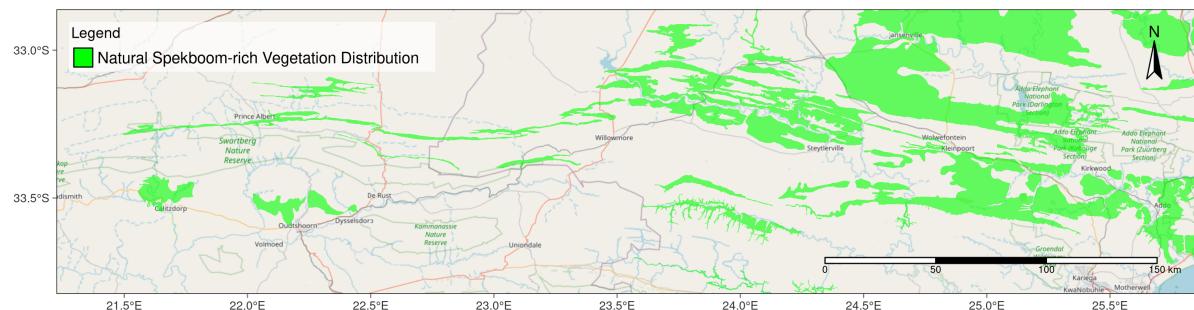


Figure 8: Map of Gamka Spekboom Thicket, Gamka Arid Spekboomveld and Paardepoort Spekboom Thicket.



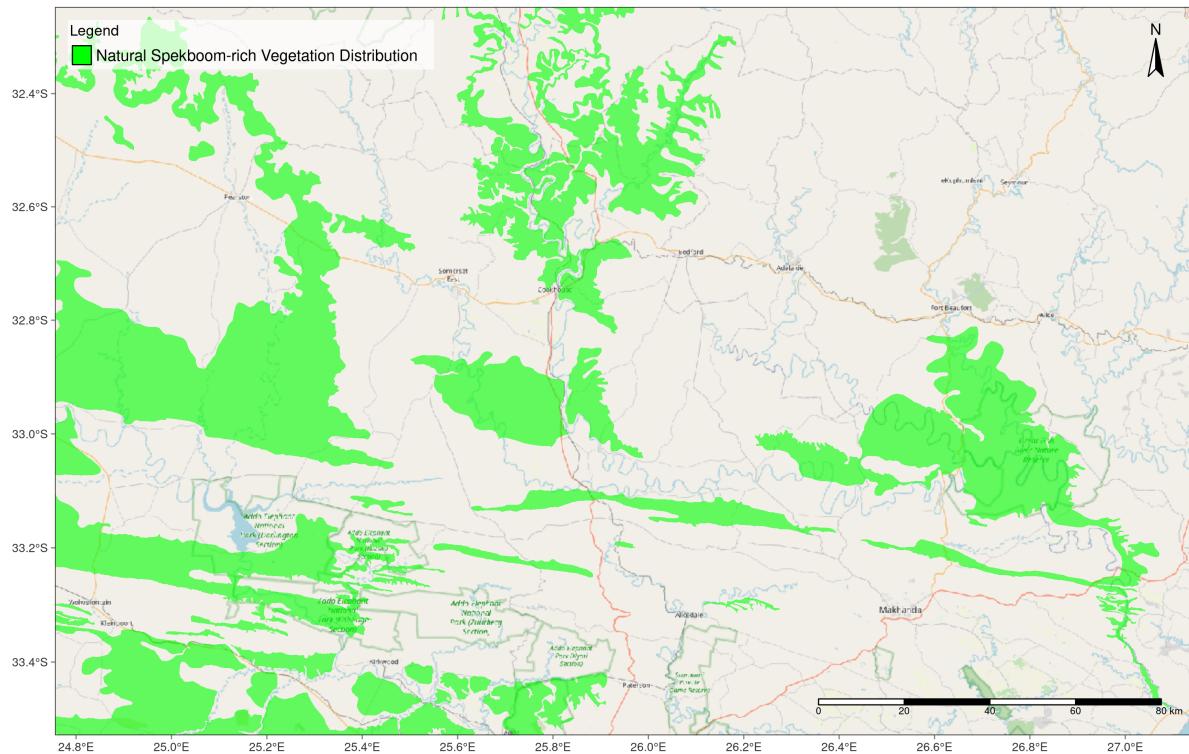


Figure 9: Map of Fish Spekboom Thicket, Albany Spekboom Thicket and Albany Spekboomveld.

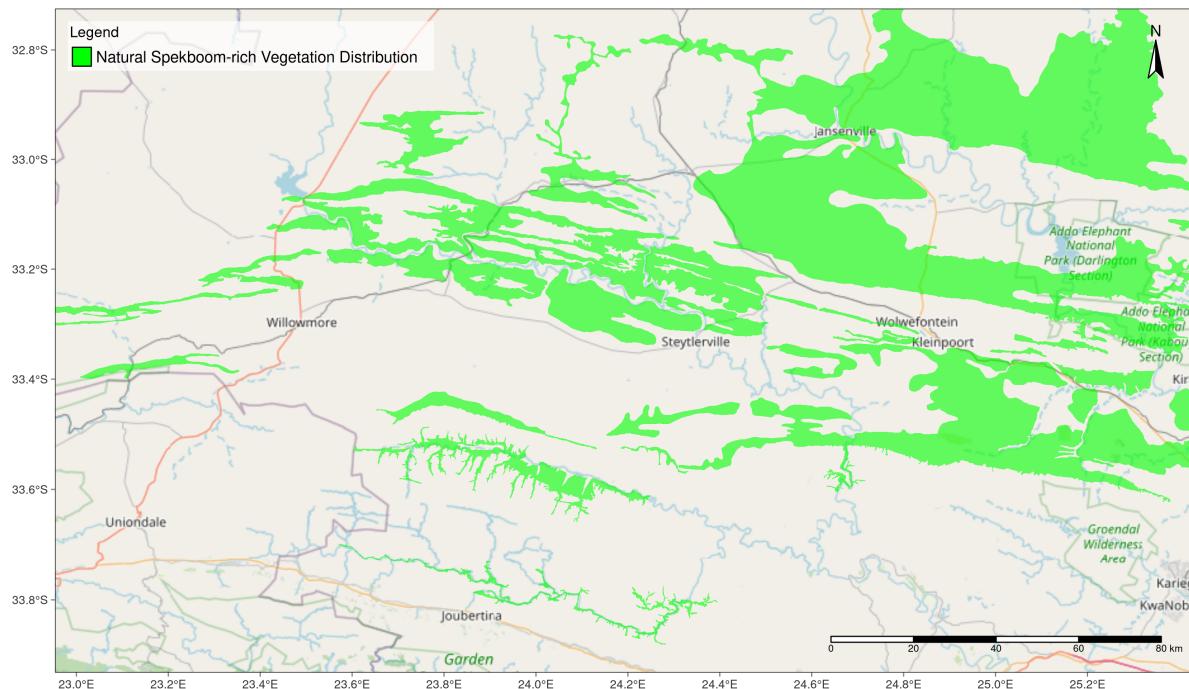


Figure 10: Map of Groot Arid Spekboomveld, Baviaans Spekboom Thicket and Gamtoos Arid Spekboomveld.



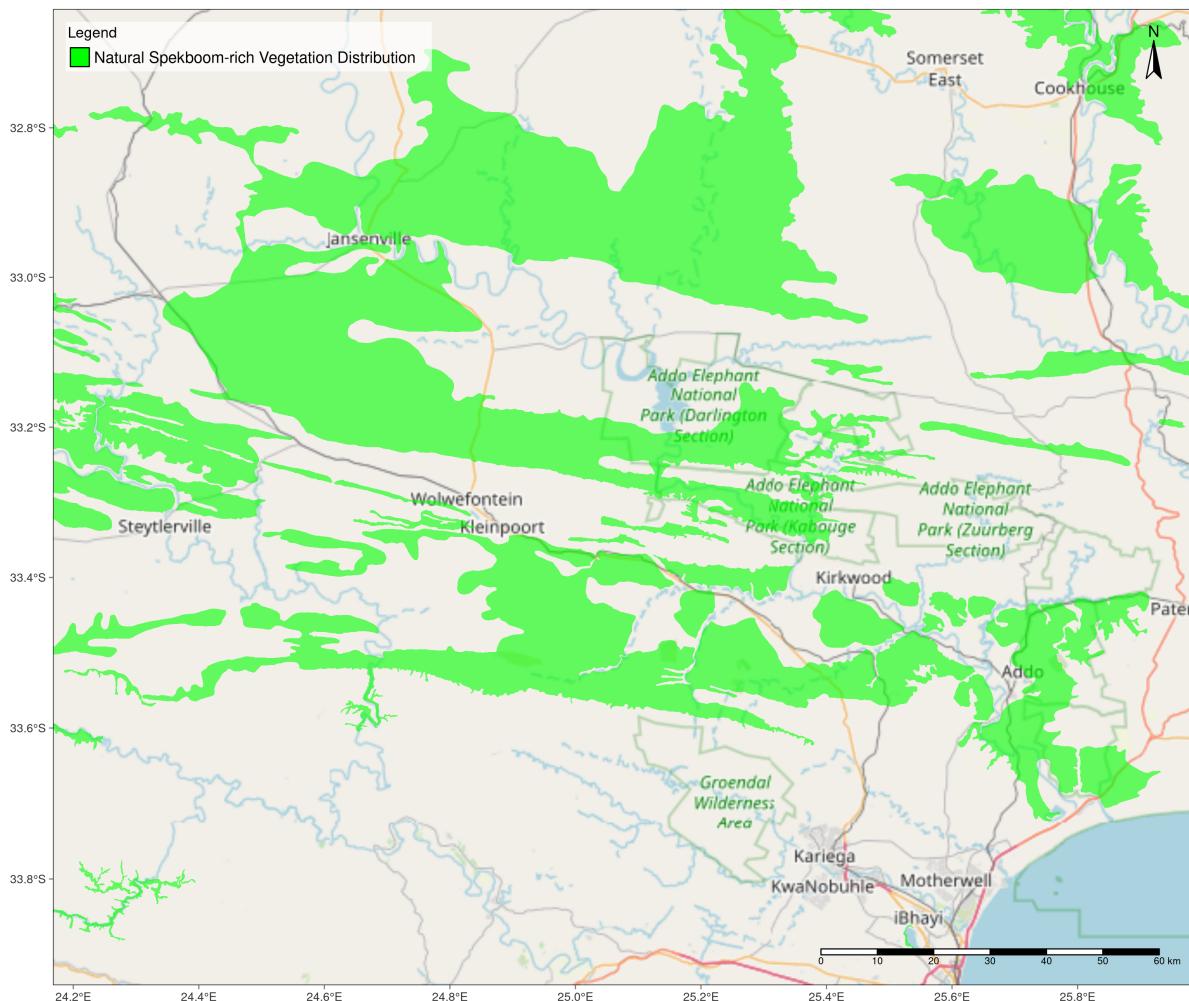


Figure 11: Map of Escarpment Spekboomveld and Escarpment Spekboom Thicket.



5 APPENDIX B - Allometric equations for some species present in Spekboom-rich vegetation



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Aloe speciosa</i>	Kirkwood	CD	22	0.81	-16.02	3.93	0.80	0.26	3.90	0.59	1.34	1.06
<i>Aloe speciosa</i>	Kirkwood	SL	22	0.74	-8.28	2.08	0.95	0.20	5.04	0.81	1.39	1.15
<i>Aloe speciosa</i>	Kirkwood	BSD	22	0.79	-6.05	1.93	0.86	0.23	4.30	0.67	1.40	1.20
<i>Aloe speciosa</i>	Kirkwood	CD.SL	22	0.83	-12.05	1.47	0.76	0.27	3.64	0.53	1.24	1.09
<i>Aloe speciosa</i>	Kirkwood	CA.SL	22	0.85	-13.31	1.10	0.72	0.30	3.36	0.47	1.22	1.08
<i>Aloe speciosa</i>	Kirkwood	CA	22	0.81	-15.55	1.97	0.80	0.26	3.90	0.59	1.34	1.07
<i>Aloe speciosa</i>	Kirkwood	BSDa	22	0.79	-5.82	0.97	0.86	0.23	4.30	0.67	1.40	1.20
<i>Aloe speciosa</i>	Kirkwood	BSDa.SL	22	0.79	-6.77	0.67	0.86	0.23	4.29	0.67	1.36	1.18
<i>Aloe striata</i>	Darlington	Hgt	15	0.74	-6.53	1.79	0.80	0.26	3.85	0.55	1.26	1.12
<i>Aloe striata</i>	Darlington	CD	15	0.60	-6.40	1.98	0.98	0.19	5.33	0.82	1.42	1.12
<i>Aloe striata</i>	Darlington	CD.H	15	0.71	-6.83	0.99	0.84	0.24	4.16	0.61	1.31	1.12
<i>Aloe striata</i>	Darlington	CA.H	15	0.68	-6.63	0.67	0.87	0.23	4.43	0.66	1.34	1.12
<i>Asparagus capensis</i>	Darlington	Hgt	16	0.12	-6.50	1.07	1.34	0.09	10.81	1.57	2.84	1.09
<i>Asparagus capensis</i>	Darlington	CD	16	0.85	-12.07	2.33	0.55	0.40	2.50	0.26	1.12	1.07
<i>Asparagus capensis</i>	Darlington	CD.H	16	0.64	-12.92	1.33	0.86	0.23	4.31	0.65	1.82	1.06
<i>Asparagus capensis</i>	Darlington	CA.H	16	0.77	-13.15	0.91	0.69	0.32	3.16	0.41	1.33	1.06
<i>Azima tetracantha</i>	Kirkwood	Hgt	11	0.54	-12.39	2.98	1.05	0.16	6.15	0.91	1.60	1.02
<i>Azima tetracantha</i>	Kirkwood	CD	11	0.92	-13.02	2.84	0.45	0.48	2.10	0.16	1.09	1.02
<i>Azima tetracantha</i>	Kirkwood	CD.H	11	0.91	-16.71	1.82	0.45	0.47	2.12	0.17	1.08	1.02
<i>Azima tetracantha</i>	Kirkwood	CA.H	11	0.95	-15.63	1.15	0.36	0.55	1.81	0.10	1.05	1.02
<i>Blepharis capensis</i> [▽]	Kirkwood	Hgt	5	0.92	-17.34	4.49	0.84	0.24	4.14	0.42	1.19	1.03
<i>Blepharis capensis</i> [▽]	Kirkwood	CD	5	1.00	-8.91	1.85	0.18	0.74	1.35	0.02	1.01	1.01
<i>Blepharis capensis</i> [▽]	Kirkwood	CD.H	5	0.99	-11.57	1.34	0.24	0.67	1.49	0.03	1.02	1.02
<i>Blepharis capensis</i> [▽]	Kirkwood	CA.H	5	1.00	-11.36	0.78	0.18	0.75	1.34	0.02	1.01	1.01
<i>Boscia oleoides</i>	Kirkwood	Hgt	14	0.41	-15.22	3.34	0.69	0.32	3.16	0.40	1.22	1.00
<i>Boscia oleoides</i>	Kirkwood	CD	14	0.76	-14.16	3.13	0.44	0.48	2.08	0.17	1.09	1.01
<i>Boscia oleoides</i>	Kirkwood	CD.H	14	0.79	-21.08	2.16	0.41	0.51	1.97	0.14	1.07	1.00



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Boscia oleoides</i>	Kirkwood	CA.H	14	0.81	-18.89	1.33	0.39	0.52	1.91	0.13	1.07	1.01
<i>Brachylaena ilicifolia</i>	Kirkwood	Hgt	13	0.95	-22.09	4.48	0.30	0.61	1.63	0.07	1.04	1.01
<i>Brachylaena ilicifolia</i>	Kirkwood	CD	13	0.90	-12.71	2.80	0.43	0.49	2.05	0.16	1.09	1.02
<i>Brachylaena ilicifolia</i>	Kirkwood	CD.H	13	0.96	-17.13	1.79	0.28	0.63	1.58	0.06	1.04	1.01
<i>Brachylaena ilicifolia</i>	Kirkwood	CA.H	13	0.94	-15.25	1.10	0.33	0.58	1.72	0.09	1.05	1.02
<i>Capparis sepiaria</i>	Kirkwood	Hgt	11	0.52	-10.61	2.53	0.82	0.25	4.04	0.55	1.27	1.01
<i>Capparis sepiaria</i>	Kirkwood	CD	11	0.89	-10.48	2.40	0.40	0.52	1.94	0.13	1.07	1.02
<i>Capparis sepiaria</i>	Kirkwood	CD.H	11	0.83	-12.73	1.44	0.49	0.44	2.28	0.20	1.10	1.02
<i>Capparis sepiaria</i>	Kirkwood	CA.H	11	0.87	-12.00	0.92	0.43	0.49	2.04	0.15	1.07	1.02
<i>Carissa haematocarpa</i>	Kirkwood	Hgt	8	0.93	-15.86	3.75	0.33	0.58	1.72	0.08	1.04	1.01
<i>Carissa haematocarpa</i>	Kirkwood	CD	8	0.86	-8.98	2.26	0.46	0.47	2.13	0.16	1.08	1.01
<i>Carissa haematocarpa</i>	Kirkwood	CD.H	8	0.91	-11.98	1.45	0.37	0.54	1.84	0.10	1.06	1.01
<i>Carissa haematocarpa</i>	Kirkwood	CA.H	8	0.89	-10.65	0.89	0.40	0.52	1.93	0.12	1.06	1.01
<i>Cotyledon velutina</i>	Kirkwood	Hgt	8	0.01	-0.28	0.32	0.88	0.22	4.50	0.58	1.30	1.01
<i>Cotyledon velutina</i>	Kirkwood	CD	8	0.83	-7.88	2.17	0.37	0.54	1.84	0.10	1.05	1.01
<i>Cotyledon velutina</i>	Kirkwood	CD.H	8	0.45	-8.76	1.09	0.66	0.33	3.01	0.32	1.17	1.01
<i>Cotyledon velutina</i>	Kirkwood	CA.H	8	0.63	-9.19	0.79	0.54	0.41	2.45	0.22	1.11	1.01
<i>Crassula mesembryanthemoides</i>	Darlington	Hgt	14	0.43	-6.49	1.29	0.64	0.34	2.91	0.35	1.19	1.07
<i>Crassula mesembryanthemoides</i>	Darlington	CD	14	0.75	-7.62	1.62	0.42	0.49	2.02	0.15	1.08	1.05
<i>Crassula mesembryanthemoides</i>	Darlington	CD.H	14	0.68	-7.79	0.85	0.48	0.45	2.23	0.20	1.11	1.05
<i>Crassula mesembryanthemoides</i>	Darlington	CA.H	14	0.72	-7.76	0.57	0.45	0.48	2.09	0.17	1.09	1.05
<i>Crassula muscosa</i>	Darlington	Hgt	17	0.85	-11.84	3.03	0.54	0.41	2.45	0.26	1.13	1.06
<i>Crassula muscosa</i>	Darlington	CD	17	0.96	-8.94	1.96	0.26	0.65	1.53	0.06	1.03	1.03
<i>Crassula muscosa</i>	Darlington	CD.H	17	0.96	-10.42	1.24	0.29	0.62	1.60	0.07	1.03	1.03
<i>Crassula muscosa</i>	Darlington	CA.H	17	0.97	-9.71	0.77	0.26	0.66	1.53	0.06	1.03	1.03
<i>Crassula ovata</i> ▽	Cambria	Hgt	21	0.84	-13.32	2.84	1.00	0.18	5.54	0.90	1.49	1.19
<i>Crassula ovata</i> ▽	Cambria	CD	21	0.65	-12.45	2.71	1.49	0.07	14.59	2.00	1.52	1.23



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Crassula ovata</i> ▽	Cambria	CD.H	21	0.87	-14.92	1.62	0.90	0.21	4.65	0.74	1.30	1.16
<i>Crassula ovata</i> ▽	Cambria	CA.H	21	0.82	-14.30	1.06	1.06	0.16	6.24	1.02	1.34	1.18
<i>Crassula perforata</i>	Darlington	Hgt	14	0.89	-11.78	2.83	0.58	0.38	2.62	0.28	1.16	1.07
<i>Crassula perforata</i>	Darlington	CD	14	0.94	-8.87	2.05	0.41	0.51	1.96	0.14	1.07	1.06
<i>Crassula perforata</i>	Darlington	CD.H	14	0.98	-10.65	1.27	0.25	0.67	1.50	0.05	1.03	1.03
<i>Crassula perforata</i>	Darlington	CA.H	14	0.98	-9.86	0.79	0.27	0.64	1.56	0.06	1.03	1.03
<i>Drosanthemum lique</i>	Calitzdorp	Hgt	5	0.00	-2.05	-0.06	1.95	0.02	41.15	2.27	2.97	1.02
<i>Drosanthemum lique</i>	Calitzdorp	CD	5	0.93	-13.59	3.05	0.52	0.42	2.38	0.16	1.09	1.02
<i>Drosanthemum lique</i>	Calitzdorp	CD.H	5	0.53	-14.55	1.75	1.34	0.09	10.75	1.07	1.49	1.01
<i>Drosanthemum lique</i>	Calitzdorp	CA.H	5	0.75	-15.29	1.24	0.97	0.19	5.26	0.56	1.26	1.01
<i>Ehretia rigida</i>	Kirkwood	Hgt	8	0.91	-13.24	2.95	0.38	0.53	1.88	0.11	1.05	1.01
<i>Ehretia rigida</i>	Kirkwood	CD	8	0.96	-11.47	2.51	0.27	0.64	1.56	0.06	1.03	1.01
<i>Ehretia rigida</i>	Kirkwood	CD.H	8	0.99	-13.18	1.43	0.13	0.81	1.24	0.01	1.01	1.01
<i>Ehretia rigida</i>	Kirkwood	CA.H	8	0.99	-12.50	0.92	0.14	0.79	1.26	0.02	1.01	1.01
<i>Euclea undulata</i>	Kirkwood	Hgt	22	0.67	-17.17	3.65	1.14	0.14	7.23	1.18	1.58	1.06
<i>Euclea undulata</i>	Kirkwood	CD	22	0.95	-11.28	2.60	0.42	0.50	2.01	0.16	1.10	1.06
<i>Euclea undulata</i>	Kirkwood	CD.H	22	0.93	-15.58	1.69	0.52	0.42	2.39	0.25	1.13	1.06
<i>Euclea undulata</i>	Kirkwood	CA.H	22	0.95	-13.87	1.04	0.43	0.49	2.04	0.17	1.09	1.05
<i>Euphorbia coerulescens</i>	Jansenville	Hgt	15	0.82	-7.24	2.18	1.05	0.16	6.18	0.96	1.83	1.24
<i>Euphorbia coerulescens</i>	Jansenville	CD	15	0.95	-9.02	2.62	0.57	0.39	2.58	0.28	1.13	1.11
<i>Euphorbia coerulescens</i>	Jansenville	CD.H	15	0.96	-8.90	1.30	0.51	0.43	2.35	0.23	1.13	1.10
<i>Euphorbia coerulescens</i>	Jansenville	CA.H	15	0.97	-8.95	0.88	0.40	0.52	1.93	0.14	1.07	1.06
<i>Euphorbia mauritanica</i>	Calitzdorp	Hgt	10	0.32	-9.57	2.17	0.84	0.24	4.14	0.56	1.26	1.01
<i>Euphorbia mauritanica</i>	Calitzdorp	CD	10	0.55	-5.86	1.52	0.68	0.32	3.13	0.37	1.25	1.03
<i>Euphorbia mauritanica</i>	Calitzdorp	CD.H	10	0.60	-10.06	1.17	0.64	0.34	2.95	0.33	1.19	1.01
<i>Euphorbia mauritanica</i>	Calitzdorp	CA.H	10	0.60	-8.36	0.68	0.65	0.34	2.95	0.33	1.20	1.02
<i>Euphorbia triangularis</i>	Kirkwood	Hgt	22	0.98	-15.19	3.18	0.35	0.56	1.79	0.11	1.05	1.04



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Euphorbia triangularis</i>	Kirkwood	CD	22	0.87	-11.65	3.00	0.81	0.25	3.95	0.60	1.29	1.12
<i>Euphorbia triangularis</i>	Kirkwood	CD.H	22	0.97	-14.18	1.62	0.42	0.50	2.00	0.16	1.08	1.06
<i>Euphorbia triangularis</i>	Kirkwood	CA.H	22	0.94	-13.22	1.06	0.54	0.41	2.46	0.27	1.13	1.08
<i>Galenia filiformis</i>	Calitzdorp	Hgt	6	0.20	-9.93	2.10	1.01	0.18	5.67	0.68	1.46	1.01
<i>Galenia filiformis</i>	Calitzdorp	CD	6	0.74	-12.27	2.52	0.58	0.38	2.63	0.22	1.11	1.01
<i>Galenia filiformis</i>	Calitzdorp	CD.H	6	0.61	-13.98	1.56	0.71	0.30	3.29	0.33	1.18	1.01
<i>Galenia filiformis</i>	Calitzdorp	CA.H	6	0.68	-13.43	0.99	0.64	0.34	2.93	0.27	1.14	1.01
<i>Grewia robusta</i>	Kirkwood	Hgt	16	0.65	-17.81	3.93	0.68	0.32	3.13	0.40	1.18	1.01
<i>Grewia robusta</i>	Kirkwood	CD	16	0.91	-11.87	2.66	0.35	0.56	1.78	0.11	1.06	1.02
<i>Grewia robusta</i>	Kirkwood	CD.H	16	0.89	-16.00	1.75	0.39	0.52	1.91	0.13	1.07	1.02
<i>Grewia robusta</i>	Kirkwood	CA.H	16	0.90	-14.31	1.07	0.36	0.56	1.80	0.11	1.06	1.02
<i>Gymnosporia polyacantha</i>	Kirkwood	Hgt	15	0.87	-18.09	3.88	0.96	0.19	5.17	0.80	1.50	1.08
<i>Gymnosporia polyacantha</i>	Kirkwood	CD	15	0.98	-13.82	3.05	0.38	0.53	1.89	0.13	1.06	1.05
<i>Gymnosporia polyacantha</i>	Kirkwood	CD.H	15	0.98	-16.55	1.79	0.39	0.53	1.90	0.13	1.06	1.05
<i>Gymnosporia polyacantha</i>	Kirkwood	CA.H	15	0.99	-15.41	1.14	0.30	0.61	1.64	0.08	1.04	1.03
<i>Jathropa capensis</i>	Kirkwood	Hgt	4	0.27	-13.31	2.82	0.78	0.27	3.72	0.30	1.16	1.00
<i>Jathropa capensis</i>	Kirkwood	CD	4	0.72	-9.82	2.22	0.48	0.45	2.22	0.12	1.05	1.00
<i>Jathropa capensis</i>	Kirkwood	CD.H	4	0.69	-15.54	1.65	0.51	0.43	2.32	0.13	1.07	1.00
<i>Jathropa capensis</i>	Kirkwood	CA.H	4	0.72	-13.23	0.97	0.48	0.45	2.22	0.12	1.06	1.00
<i>Lycium cinereum</i>	Calitzdorp	Hgt	8	0.90	-7.10	1.73	0.42	0.50	2.00	0.13	1.07	1.03
<i>Lycium cinereum</i>	Calitzdorp	CD	8	0.90	-10.61	2.28	0.42	0.50	2.00	0.13	1.06	1.02
<i>Lycium cinereum</i>	Calitzdorp	CD.H	8	0.95	-9.18	1.04	0.30	0.61	1.65	0.07	1.03	1.02
<i>Lycium cinereum</i>	Calitzdorp	CA.H	8	0.95	-9.63	0.72	0.31	0.60	1.66	0.07	1.03	1.02
<i>Lycium ferocissimum</i> ▽	Cambria	Hgt	24	0.64	-9.67	2.11	0.80	0.26	3.89	0.59	1.30	1.07
<i>Lycium ferocissimum</i> ▽	Cambria	CD	24	0.62	-5.28	1.29	0.82	0.25	4.05	0.62	1.30	1.15
<i>Lycium ferocissimum</i> ▽	Cambria	CD.H	24	0.66	-7.48	0.85	0.77	0.27	3.68	0.54	1.26	1.10
<i>Lycium ferocissimum</i> ▽	Cambria	CA.H	24	0.65	-6.56	0.52	0.79	0.26	3.78	0.57	1.27	1.12



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Malephora lutea</i>	Calitzdorp	Hgt	9	0.39	-5.77	2.06	0.94	0.20	4.98	0.69	1.25	1.06
<i>Malephora lutea</i>	Calitzdorp	CD	9	0.93	-6.88	1.54	0.31	0.60	1.67	0.08	1.04	1.03
<i>Malephora lutea</i>	Calitzdorp	CD.H	9	0.90	-7.93	1.14	0.38	0.53	1.87	0.11	1.06	1.04
<i>Malephora lutea</i>	Calitzdorp	CA.H	9	0.93	-7.47	0.67	0.31	0.60	1.66	0.07	1.04	1.03
<i>Mesembryanthemum guerichianum</i>	Pearston	Hgt	3	0.98	-7.46	1.73	0.08	0.87	1.15	0.00	1.00	1.00
<i>Mesembryanthemum guerichianum</i>	Pearston	CD	3	0.30	-8.48	1.87	0.53	0.41	2.42	0.09	1.05	1.00
<i>Mesembryanthemum guerichianum</i>	Pearston	CD.H	3	0.84	-9.52	1.15	0.26	0.66	1.52	0.02	1.01	1.00
<i>Mesembryanthemum guerichianum</i>	Pearston	CA.H	3	0.71	-9.77	0.80	0.34	0.57	1.76	0.04	1.02	1.00
<i>Panicum maximum</i> [▽]	Kirkwood	Hgt	8	0.63	-14.26	2.60	0.86	0.23	4.34	0.56	1.31	1.02
<i>Panicum maximum</i> [▽]	Kirkwood	CD	8	0.85	-12.34	2.42	0.55	0.40	2.49	0.22	1.11	1.03
<i>Panicum maximum</i> [▽]	Kirkwood	CD.H	8	0.82	-14.37	1.38	0.60	0.37	2.71	0.27	1.14	1.02
<i>Panicum maximum</i> [▽]	Kirkwood	CA.H	8	0.85	-14.85	0.90	0.55	0.40	2.52	0.23	1.12	1.02
<i>Pappea capensis</i>	Kirkwood	Hgt	20	0.93	-19.01	4.07	0.53	0.41	2.43	0.26	1.13	1.04
<i>Pappea capensis</i>	Kirkwood	CD	20	0.98	-12.07	2.79	0.27	0.64	1.56	0.07	1.03	1.03
<i>Pappea capensis</i>	Kirkwood	CD.H	20	0.98	-15.21	1.68	0.31	0.60	1.66	0.08	1.04	1.03
<i>Pappea capensis</i>	Kirkwood	CA.H	20	0.98	-13.82	1.05	0.27	0.64	1.57	0.07	1.03	1.03
<i>Plumbago auriculata</i> [▽]	Cambria	Hgt	21	0.66	-11.49	2.59	0.84	0.24	4.13	0.63	1.40	1.06
<i>Plumbago auriculata</i> [▽]	Cambria	CD	21	0.58	-9.69	2.00	0.92	0.21	4.79	0.76	1.79	1.07
<i>Plumbago auriculata</i> [▽]	Cambria	CD.H	21	0.80	-14.03	1.47	0.64	0.34	2.91	0.37	1.26	1.05
<i>Plumbago auriculata</i> [▽]	Cambria	CA.H	21	0.75	-12.73	0.89	0.72	0.30	3.33	0.46	1.41	1.05
<i>Portulacaria afra</i>	Kirkwood	Hgt	42	0.85	-12.05	3.01	0.93	0.20	4.94	0.83	1.40	1.22
<i>Portulacaria afra</i>	Kirkwood	CD	42	0.94	-10.40	2.62	0.60	0.37	2.72	0.34	1.15	1.14
<i>Portulacaria afra</i>	Kirkwood	CD.H	42	0.93	-11.75	1.46	0.63	0.35	2.85	0.37	1.17	1.14
<i>Portulacaria afra</i>	Kirkwood	CA.H	42	0.94	-11.15	0.94	0.58	0.38	2.65	0.33	1.15	1.13
<i>Psilocaulon junceum</i>	Calitzdorp	Hgt	8	0.84	-16.04	4.54	0.71	0.30	3.28	0.37	1.16	1.02
<i>Psilocaulon junceum</i>	Calitzdorp	CD	8	0.96	-10.21	2.28	0.36	0.55	1.82	0.10	1.05	1.04
<i>Psilocaulon junceum</i>	Calitzdorp	CD.H	8	0.94	-12.50	1.57	0.41	0.51	1.97	0.13	1.06	1.03



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Psilocaulon junceum</i>	Calitzdorp	CA.H	8	0.95	-11.38	0.93	0.38	0.53	1.87	0.11	1.05	1.03
<i>Ptaeroxylon obliquum</i>	Kirkwood	Hgt	20	0.90	-23.93	4.61	0.96	0.19	5.14	0.82	1.39	1.09
<i>Ptaeroxylon obliquum</i>	Kirkwood	CD	20	0.94	-12.71	2.87	0.78	0.27	3.71	0.54	1.29	1.17
<i>Ptaeroxylon obliquum</i>	Kirkwood	CD.H	20	0.98	-18.06	1.87	0.48	0.45	2.23	0.21	1.12	1.07
<i>Ptaeroxylon obliquum</i>	Kirkwood	CA.H	20	0.97	-15.82	1.14	0.55	0.40	2.52	0.28	1.15	1.10
<i>Pteronia incana</i>	Calitzdorp	Hgt	6	0.75	-15.48	3.97	0.94	0.20	5.02	0.59	1.32	1.02
<i>Pteronia incana</i>	Calitzdorp	CD	6	0.95	-10.21	2.31	0.44	0.48	2.08	0.13	1.06	1.03
<i>Pteronia incana</i>	Calitzdorp	CD.H	6	0.93	-12.91	1.56	0.49	0.44	2.25	0.16	1.09	1.02
<i>Pteronia incana</i>	Calitzdorp	CA.H	6	0.95	-11.68	0.94	0.44	0.48	2.08	0.13	1.07	1.03
<i>Putterlickia pyracantha</i>	Kirkwood	Hgt	15	0.68	-10.06	2.35	0.96	0.19	5.20	0.80	1.42	1.07
<i>Putterlickia pyracantha</i>	Kirkwood	CD	15	0.76	-6.59	1.69	0.83	0.25	4.07	0.59	1.45	1.12
<i>Putterlickia pyracantha</i>	Kirkwood	CD.H	15	0.78	-8.79	1.06	0.79	0.26	3.82	0.54	1.37	1.09
<i>Putterlickia pyracantha</i>	Kirkwood	CA.H	15	0.78	-7.90	0.66	0.79	0.26	3.80	0.54	1.40	1.10
<i>Rhigozum obovatum</i>	Oudtshoorn	Hgt	8	0.80	-11.82	2.73	0.76	0.28	3.61	0.43	1.24	1.03
<i>Rhigozum obovatum</i>	Oudtshoorn	CD	8	0.88	-11.96	2.65	0.58	0.38	2.63	0.25	1.16	1.03
<i>Rhigozum obovatum</i>	Oudtshoorn	CD.H	8	0.89	-12.70	1.43	0.55	0.40	2.52	0.23	1.15	1.02
<i>Rhigozum obovatum</i>	Oudtshoorn	CA.H	8	0.90	-12.39	0.94	0.53	0.41	2.43	0.21	1.14	1.03
<i>Ruschia multiflora</i>	Calitzdorp	Hgt	6	0.67	-6.12	1.49	0.53	0.41	2.43	0.19	1.10	1.02
<i>Ruschia multiflora</i>	Calitzdorp	CD	6	0.87	-7.13	1.58	0.34	0.57	1.74	0.08	1.04	1.02
<i>Ruschia multiflora</i>	Calitzdorp	CD.H	6	0.87	-7.51	0.88	0.33	0.58	1.72	0.07	1.04	1.01
<i>Ruschia multiflora</i>	Calitzdorp	CA.H	6	0.90	-7.43	0.58	0.30	0.61	1.63	0.06	1.03	1.01
<i>Schotia afra</i>	Kirkwood	Hgt	19	0.63	-15.61	3.38	1.44	0.08	13.16	1.84	1.87	1.07
<i>Schotia afra</i>	Kirkwood	CD	19	0.89	-11.06	2.62	0.79	0.26	3.79	0.56	1.26	1.12
<i>Schotia afra</i>	Kirkwood	CD.H	19	0.92	-16.23	1.76	0.65	0.34	2.98	0.38	1.18	1.07
<i>Schotia afra</i>	Kirkwood	CA.H	19	0.93	-14.34	1.08	0.61	0.36	2.78	0.34	1.14	1.08
<i>Vachellia karoo</i> ▽	Cambria	Hgt	15	0.91	-19.14	3.65	0.57	0.39	2.58	0.28	1.15	1.04
<i>Vachellia karoo</i> ▽	Cambria	CD	15	0.95	-21.26	4.07	0.42	0.50	2.02	0.16	1.09	1.03



Table 4: Parameters of all allometric models developed for common species within spekboom thicket and adjacent vegetation.

Species	Location	x.var [§]	n	r ²	log(a) [†]	b [†]	σ [†]	LC [†]	UC [†]	MSE	Duan [‡]	MB [*]
<i>Vachellia karoo</i> [▽]	Cambria	CD.H	15	0.97	-20.94	2.00	0.35	0.56	1.78	0.11	1.05	1.03
<i>Vachellia karoo</i> [▽]	Cambria	CA.H	15	0.97	-20.91	1.35	0.33	0.58	1.72	0.09	1.05	1.02

[§] Predictor variable where Hgt/H = plant height (cm), CD = mean crown diameter, CD.H = CD.Hgt, CA.H = $\pi \cdot (\frac{CD}{2})^2 \cdot H$ SL = stem length up to base of rosette for *Aloe speciosa*, BSD = basal stem diameter, BSA = basal stem area.

[†] To get an individual estimate use the power function $y_n = ax^b$ and substitute $a = \exp(\log(a))$ and b . This estimate, naive y (y_n), can be corrected following Zou *et al.* (2009) and Nickless *et al.* (2011) to derive corrected y_c with $y_c = \exp(\ln(y_n) + \frac{\sigma^2}{2})$. The Lower (LC) and Upper confidence limits (UC) can be obtained by multiplying y_c with the tabled LC and UC values.

[‡] Duan (1983)'s Smearing Estimate correction factor to arrive at $y_c = y_n \cdot cf_{duan}$.

^{*} Shen and Zhu (2008)'s Minimum Bias (MB) correction factor to arrive at $y_c = y_n \cdot cf_{MB}$.

[▽] Models are based on dry weight instead of freshly felled weight (no need for applying a dry:wet ratio).

