Ministry for Primary Industries
Manatū Ahu Matua

Improved allometric functions for Scotch broom and tauhinu

Draft Final Report

MPI Technical Paper No: 2018/34

Prepared for Gerald Rys, Science Policy Group

by Tomás Easdale, Fiona Carswell, Larry Burrows, Brian Karl,
Landcare Research; Grant Pearce, Matt Scott, Scion

ISBN No: 978-1-77665-899-2 (online)
ISSN No:

February 2015

New Zealand Government

Disclaimer

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries website at
http://www.mpi.govt.nz/news-resources/publications.aspx

Contents

Page

Executive Summary

Despite shrubs being an important component of early-successional vegetation, existing allometries for converting shrub volume to carbon (for use in the New Zealand Emissions Trading Scheme) are often based on data from a few locations and are of narrow scope for reliable predictions. Because Emissions Trading Scheme participants are from all over New Zealand, and have regenerating lands covered with a variety of shrub species, there is a need for improved shrub allometries. Improved allometries increase the accuracy of carbon assignment (i.e. as "carbon credits") based on easily collected field data. We collected new biomass data for Scotch broom (*Cytisus scoparius*) and tauhinu (*Ozothamnus leptophyllus*), and combined this new information with existing data to derive improved allometric relationships for each of these two common species. New harvests were conducted along regeneration/age sequences at two sites for each species. All above-ground biomass was harvested within 4 × 4 m plots and total dry biomass was estimated on the basis of the total weight of fresh biomass and the moisture content of subsamples. Tree ring counts from the largest stems on each plot provided an estimate of stand age. Different potential allometric functions were tested for their ability to predict slope-corrected shrubland carbon (CO_2e) as a linear or non-linear function of either the volume, height, or stand age of shrubland.

We found that:

- Mean canopy height can be used to accurately predict carbon stocks both in broom and tauhinu. Predictions based on basal area or shrubland volume are similarly accurate to those based on mean canopy height, such that the additional work required to measure them is not justified by greater accuracy.
- The relationship between aboveground carbon and stand age is inherently more variable than that with mean height but this relationship is valuable in that it allows estimation of sequestration rates as a function of stand age. We provide equations to predict aboveground shrubland carbon for broom and tauhinu as a function of mean canopy height and stand age. On average, carbon stocks for stands with mean height of 2 m store 43 tonnes of CO_2e per hectare for broom and 87 tonnes of CO_2e per hectare for tauhinu.
- Differences between species are clear and justify having specific allometries for main shrubland types. Broom typically produces canopies with low carbon density but sequesters carbon rapidly when stands are young. Tauhinu canopies have greater carbon density and appear to increase sequestration rates in later successional stages.

1 Introduction

Shrublands cover large areas of New Zealand (Trotter et al. 2005) and often represent early-successional stages of regenerating tall forest. They establish spontaneously (with little or no capital investment) and relatively rapidly, and even where composed of exotic species they can act as effective nurse crops promoting tree establishment and succession to forest (Burrows et al. 2015). Owners of post-1989 'forest land' can currently claim carbon credits for regenerating shrubland within New Zealand's Emissions Trading Scheme (ETS). Yet, little is known about carbon accumulation in shrublands relative to forests and uncertainties exist regarding the actual sequestration rates of early-successional vegetation (Carswell et al 2014).

The carbon stocks of shrublands are often estimated by measuring shrubland volume and converting it to carbon by use of allometries that relate canopy volume or height to above-ground carbon (i.e. using pre-calculated carbon stock tables). These allometries can be specific to particular shrubland types. Scotch broom (*Cytisus scoparius*), hereafter referred to as "broom", and tauhinu (*Ozothamnus leptophyllus*) are common species that dominate two of nine shrubland types frequently encountered on sites experiencing reversion to indigenous vegetation (Payton et al. 2009), and two of six shrubland types recognised within the ETS for owners of regenerating indigenous forests (Ministry for Primary Industries 2012). The allometric relationships that are available to calculate carbon were derived from small datasets collected at only one site per species (Beets et al 2001; Carswell et al 2006) and we now know that allometric relationships are the main source of uncertainty when estimating the carbon stock of shrublands (Mason et al. 2014). Here, we provide new allometric relationships for broom and tauhinu by combining the existing harvest data collected in recent SLMACC-funded research with new data collected in this project at four additional sites (two for each species).

Because shrubland height and volume are relatively crude measurements, there is a question of whether they provide sufficiently accurate estimates of shrubland carbon (e.g. Conti et al. 2013; Mason et al. 2014). Thus, we also investigate whether more intensive measurements of stem basal area and stem density can enhance the accuracy of carbon stock estimations for shrublands.

2 Methods

Pre-existing data on shrubland biomass and volume were available from regeneration sequences at Dyers Pass, Hawkswood and Glenthorne for broom and from Cape Jackson for tauhinu (Table 1). The Hawkswood dataset originally consisted of 29 plots, from early-successional broom stands to more advanced broom-broadleaved regeneration stands where broom was present only as an understorey remnant (Carswell et al. 2014). Here, we use data from that study for just the 15 early-successional plots with at least 50% crown cover of broom. Similarly, for Glenthorne, we use data from only the 12 of 15 plots where the crown cover of broom was at least 50%.

Two additional sampling sites were selected for each species, to cover other regions where these species are commonly occurring. The extensive areas of broom (i.e. tens of hectares or greater) are almost entirely in the South Island (Carswell et al. 2014; Clayson Howell, DOC, pers. comm.) and existing data had been collected in Canterbury. Thus, we chose to sample at Turangi in the central North Island and Nokomai in Southland. Although tauhinu is present as individual plants or isolated clumps throughout much of eastern New Zealand, it is most extensive in the north of the South Island (Bascand & Jowett 1982). We therefore targeted harvests at White Rock and Te Hapu, in Martinborough and Golden Bay respectively (Table 1, Fig. 1).

Table 1: List of sample sites and some of their characteristics

Sample site	Region	Species	Area of harvest	Date of harvest	Number of plots	Mean slope
Dyers Pass	Banks Peninsula	Broom	5 × 5m	2000	14	30°
Hawkswood	North Canterbury	Broom	4 × 1m	March 2013	15	33°
Glenthorne	West Canterbury	Broom	4 × 1 m	Oct 2012	12	11°
Turangi	Taupo	Broom	4 × 4 m	2014	10	2°
Nokomai	Southland	Broom	4 × 4 m	2014	10	10°
Cape Jackson	Marlborough Sounds	Tauhinu	5 × 5 m	2005	13	8°
Te Hapu	Golden Bay	Tauhinu	4 × 4 m	2014	11	16°
White Rock	Martinborough	Tauhinu	4 × 4 m	2014	12	5°

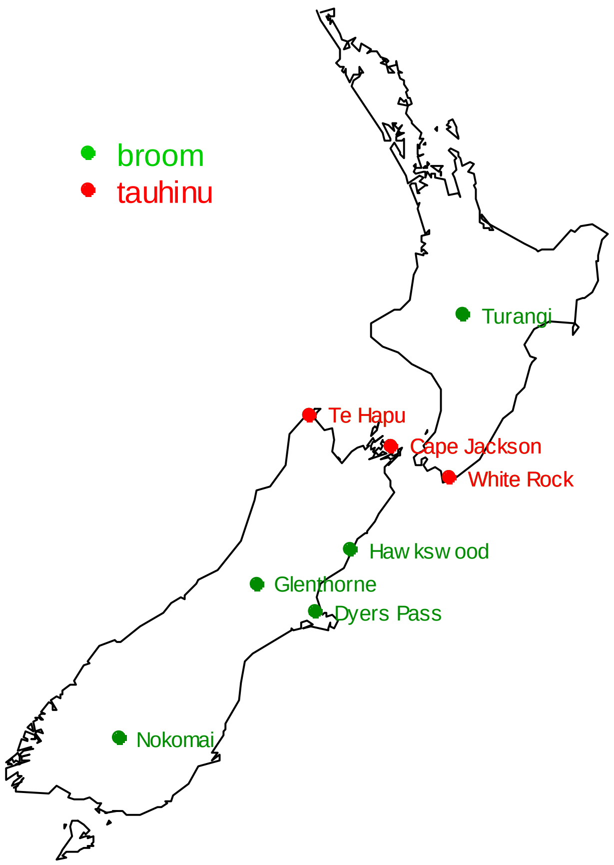


Figure 1: Location of sample sites.

At each site, at least 10 plots of 4 × 4 m were subjectively located within uniform areas of shrubland and spanning the full range of heights present. This aimed to capture a regeneration sequence, given that height is often commensurate with age. Plots spanned the range of heights from individual plants of c. 50 cm height to continuous shrubland of c. 3.5 m height without excessively sampling any particular height. Stands were often fully stocked by either broom or tauhinu and sometimes these were combined with saplings of forest species.

Canopy height (m) was measured on each of nine intersection points of a 1 × 1m grid overlaid on the plot. In two early successional plots that were not fully stocked, none of the nine measurement points overlapped with any canopy. In these two cases, we measured the height of all individual shrubs within the plot and estimated mean canopy height (H) as the mean of those heights. Percent woody cover was visually estimated across the whole plot (accounting for the shrubs and also the forest species saplings). The average slope angle was measured along the predominant aspect of the plot using a clinometer. This enabled slope-correction of all estimates of shrubland carbon, canopy volume, basal area and stem counts used in the analysis.

All above-ground plant material lying within the 4 × 4 m plot was first clipped along the lateral boundaries and then cut at ground level. All harvested fresh biomass was weighed on-site (Fig. 2) in separate components ((1) foliage plus twigs and (2) live stems of the target species, (3) dead wood, (4) other species combined). A subsample of each component in each plot was returned to the laboratory for moisture determination.

Basal discs were cut from the largest three broom or tauhinu stems found inside or imediately adjacent to the plot. Tree rings were counted both in the field ('wet age') and in the laboratory on sanded discs ('lab age') to estimate the age of the stand. Discs with a missing or rotten centre were not used.

Figure 2: Harvesting, sorting and weighing plant material of broom shrublands in Turangi.

Stand age was estimated as that of the oldest stem for the plot. Estimates that relied on lab age were only marginally older than estimates that relied on wet age (0.5 year on average) and we opted to use lab estimates on subsequent analysis.

To investigate whether basal diameter and stem density measurements can enhance the accuracy of carbon stock estimations for shrublands, we measured the basal diameter of all stems at 10 cm above ground level at one site for each species (Te Hapu for tauhinu and Turangi for broom).

2.1 Data analysis

We first investigated allometric relationships between carbon (as determined from shrubland plot biomass and expressed as CO_2 equivalent) and the shrublands' canopy volume, mean canopy height and stand age. The dry biomass of each harvested plot resulted from combining the harvested fresh biomass (both for live and dead components), the ratio of dry-to-fresh biomass of a subsample, and the area of the harvest plot. In addition, biomass was slope-corrected and scaled to CO_2 equivalents with a simple stoichiometric conversion as follows:

$$Shrubland\ CO_2\mathrm{e}_{slope\ corr.}\ (kg\ m^{-2}) =$$

$$\frac{Fresh\ biomass_{plot}(\mathrm{kg})}{area_{plot}\ (m^2)} \times \frac{Dry\ biomass_{subsample}}{Fresh\ biomass_{subsample}} \times \cos\ (\alpha) \times \frac{3.667}{2}. \qquad (1)$$

Because the area of harvested plots was not uniform across locations (Table 1), shrubland canopy volume ($V_{slope\ corr.}$) was estimated as the cubic volume typically found in one square metre. This variable accounted for the woody cover within the plot, the slope of the terrain (α) and the mean canopy height ($\overline{H}$) within the plot (the mean height from measurements at nine intersection points), as follows:

$$V_{slope\ corr.} = \frac{\%\ woody\ cover}{100} \times \cos\ (\alpha) \times\ \overline{H}\ . \qquad (2)$$

Three early-successional plots at Cape Jackson had crown widths measured for each individual shrub instead of total woody cover. For these plots, we computed the proportion woody cover ($\frac{\%\ woody\ cover}{100}$) required in equation (2) as the ratio of the total area projected by shrub crowns to the area of the plot.

We tested various shapes of relationships (linear, exponential, power, logarithmic and Gompertz) between $Shrubland\ CO_2$e and each predictor ($\overline{H}$, $V_{slope\ corr.}$, stand age). Functions were fitted with non-linear mixed effects models with a random effect for sample site, using the *nlme* command in the R statistical computing environment (version 2.15.2; R Development Core Team 2009). The most parsimonious models describing the relationship were selected using Akaike's Information Criterion for small samples (AICc). Lower AICc values indicate that a given model has greater statistical support to represent the data. Differences in AICc (ΔAICc) of < 2 mean models are more or less equivalent, differences of 4-7 units mean models are clearly distinguishable and models with AICc values > 10 units apart are definitely different (Bolker 2008). The "goodness of fit" of these models was also assessed by the coefficient of determination, r^2, of a linear regression between 'observed' and predicted values of CO_2e, and by the slope of that same regression, which gives an indication of model bias.

Models can be compared by AICc only when the response variable is exactly the same (thus they cannot be compared across species where the underlying data are different). The explanatory power of both stem basal area (the total cross sectional area of stems divided by plot area) and stem count was also compared against canopy volume, mean canopy height and stand age using data from Te Hapu and Turangi (the two sites that had all five candidate explanatory variables measured on them). Both stem basal area and stem count were slope corrected.

3 Results

3.1 New allometric relationships for broom and tauhinu

The relationships between slope-corrected carbon stocks and the measured variables are shown in Figure 3. Broom-dominated communities have a lower carbon stock than tauhinu for a given height and crown volume (Fig. 3a, c). However, the amount of carbon accumulated per unit time (i.e. the sequestration rate) is similar or slightly higher in broom than in tauhinu (Fig. 3b). Visual examination of the relationships between shrubland carbon and each of the tested explanatory variables in each species shows that the cloud of data points overlap among sample sites (Figs 4 and 5) and suggests that, broadly, they all derive from the same underlying relationships.

The allometric relationship with shrubland carbon is generally linear (or with minor curvature) when height is the predictor variable, moderately convex when shrubland volume is the predictor variable, and either asymptotic or exponential with stand age (Figs. 3, 4 & 5). When statistically judged by their AICc values, power and Gompertz functions are often better suited to describe these relationships than linear, logarithmic or exponential models (Table 2).

For broom, we find that shrubland carbon is best predicted using mean canopy height with moderately lower predictive support for shrubland volume (ΔAICc = 6). Stand age is not a good predictor of carbon stock. For tauhinu, shrubland carbon is also best predicted using mean canopy height with moderately lower predictive support for shrubland volume and stand age (ΔAICc = 7 in either case).

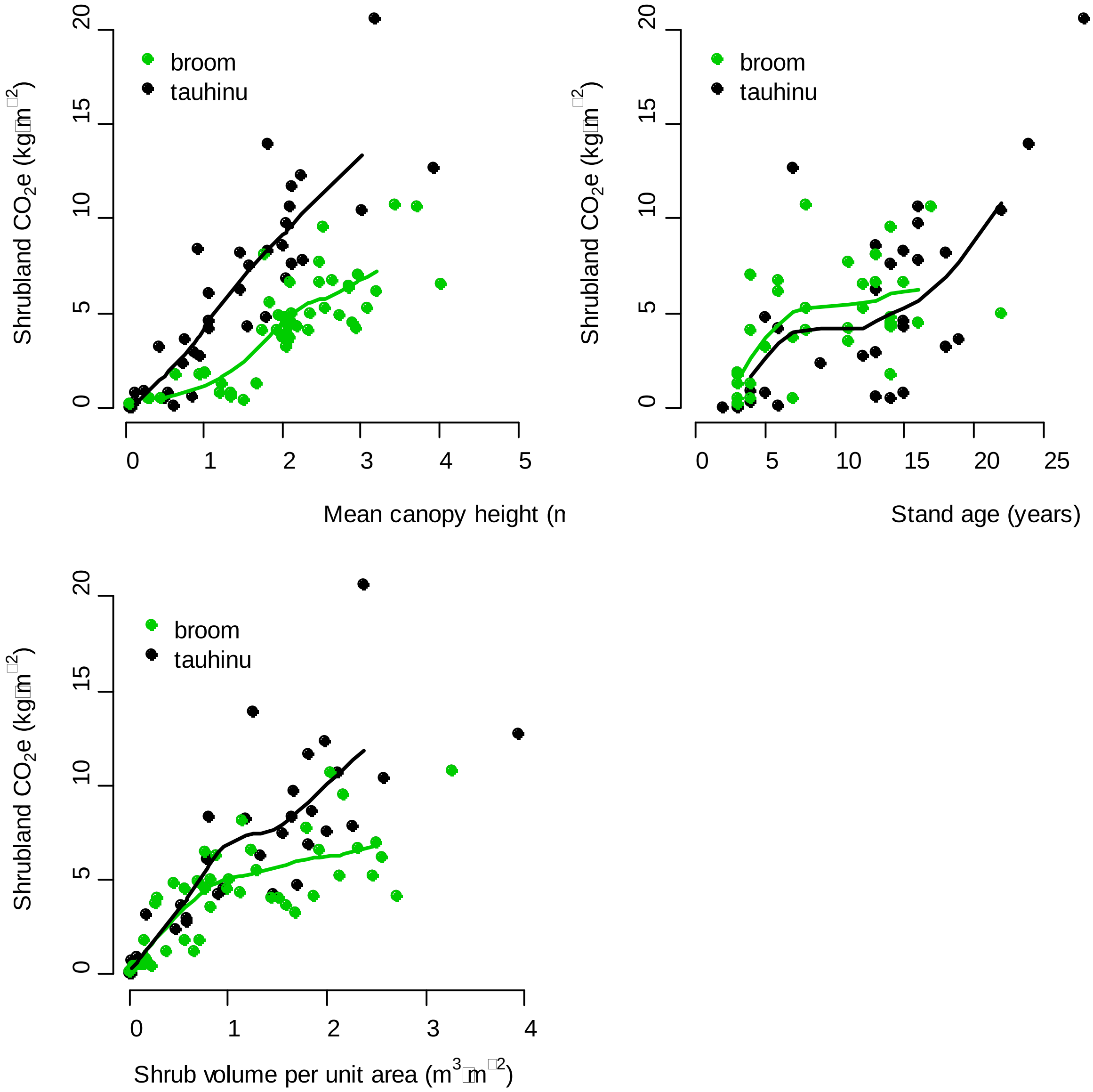


Figure 3: Shrubland carbon (measured as CO_2 e) for all plots of broom (sampled at five sites) and tauhinu (sampled at three sites) as a function of (a) mean canopy height, (b) stand age and (c) shrubland volume. Loess regression lines summarise the separate relationships for broom and tauhinu.

Table 2: Comparison of models describing allometric relationships between slope-corrected aboveground carbon (in CO_2 e kg m^{-2}) and each of three predictors for broom and tauhinu. Lower AICc values indicate stronger statistical support. Fitted models are shown only for the best supported models for each species and predictor (those within 2 AICc units of that with the lowest AICc value). Fitted parameters apply only to the measurement units indicated in the table. Values for AICc, r^2 and *Regr. slope* rely on the same plot data (*n* = 46 for broom and *n* = 23 for tauhinu) and thus can be compared within each species. Parameters for models fitted for height or volume utilise additional data from plots that were not aged (*n* = 59 for broom and *n* = 36 for tauhinu).

Species	Predictor	Model	AICc	r^2	Regr. slope*	Fitted model
Broom	Mean height (m)	linear	199.1	0.57	1	$-0.5311 + 2.434 \times \overline{\mathrm{H}}$
		power	199.1	0.57	1	$2.0198 \times \overline{\mathrm{H}}^{1.0995}$
		Gompertz	200.1	0.58	1	$8.6526 \times e^{-e^{1.8272 - 1.1133 \times \overline{\mathrm{H}}}}$
		exponential	206.1	0.51	1	
		logarithmic	209.7	0.46	1	
	Volume (m^3 m^{-2})	Power	204.9	0.52	1	$4.6742 \times \mathrm{Vol}^{0.4791}$
		linear	207.3	0.52	1	
		Gompertz	208.3	0.5	1	
		logarithmic	210.6	0.45	1	
		exponential	211	0.48	1.01	
	Age (years)	Gompertz	222.6	0.34	1	$6.0253 \times e^{-e^{2.4844 - 0.6731 \times \mathrm{Age}}}$
		logarithmic	224.3	0.26	1	$-0.4249 + 2.4815 \times \log(\mathrm{Age})$
		power	226.4	0.23	1	
		linear	228.7	0.19	1	
		exponential	230.5	0.16	1	
Tauhinu	Mean height (m)	linear	119.5	0.77	1	$-0.2228 + 4.486 \times \overline{\mathrm{H}}$
		power	119.5	0.77	1	$4.4427 \times \overline{\mathrm{H}}^{0.9804}$
		Gompertz	120.3	0.79	1	$16.412 \times e^{-e^{1.3069 - 0.9434 \times \overline{\mathrm{H}}}}$
		exponential	130.0	0.65	1	
		logarithmic	132.1	0.61	1	
	Volume (m^3 m^{-2})	power	126.6	0.69	1	$6.1136 \times \mathrm{Vol}^{0.6725}$
		Gompertz	128.6	0.7	1	$13.333 \times e^{-e^{0.9996 - 1.1733 \times \mathrm{Vol}}}$
		linear	129.2	0.65	1	
		logarithmic	136.9	0.54	1.01	
		exponential	138.0	0.51	1	
	Age (years)	exponential	126.7	0.69	1	$1.734 \times e^{0.0871 \times \mathrm{Age}}$
		Gompertz	126.8	0.69	1	$304791 \times e^{-e^{2.5 - 0.0083 \times \mathrm{Age}}}$
		power	128.6	0.66	1	$0.1765 \times \mathrm{Age}^{1.3743}$
		linear	129.7	0.64	1	
		logarithmic	135.4	0.57	1.01	

*Regr. slope = the slope of a linear regression between fitted and observed values – any major deviation from 1 would indicate bias in the fitted model.

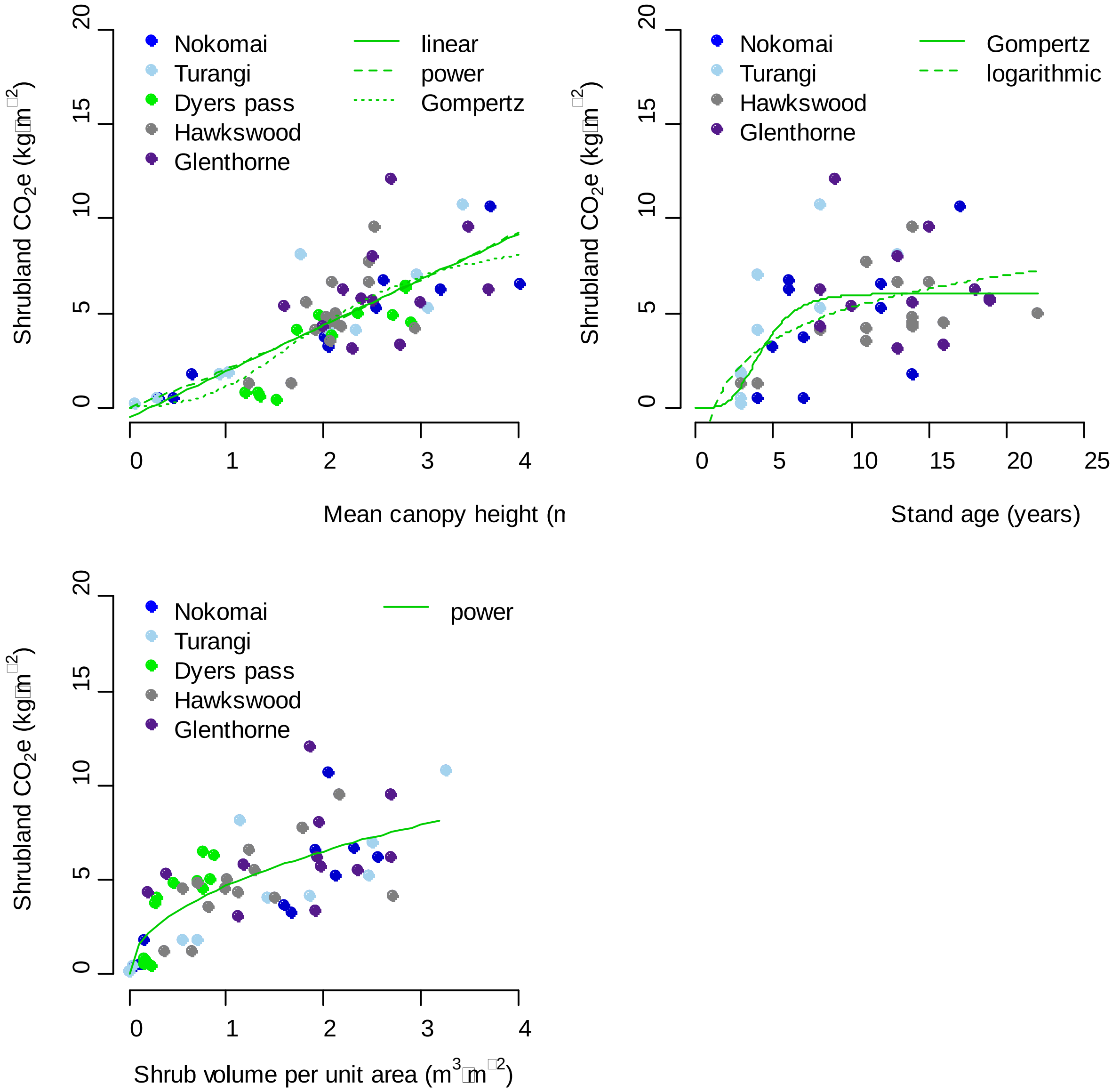


Figure 4: Broom shrubland carbon (measured as CO_2 e) as a function of mean canopy height, stand age and shrubland volume. Note that in addition to height, shrubland volume also takes account of cover and slope. Regression lines are shown for the best supported models only with equations given in Table 2.

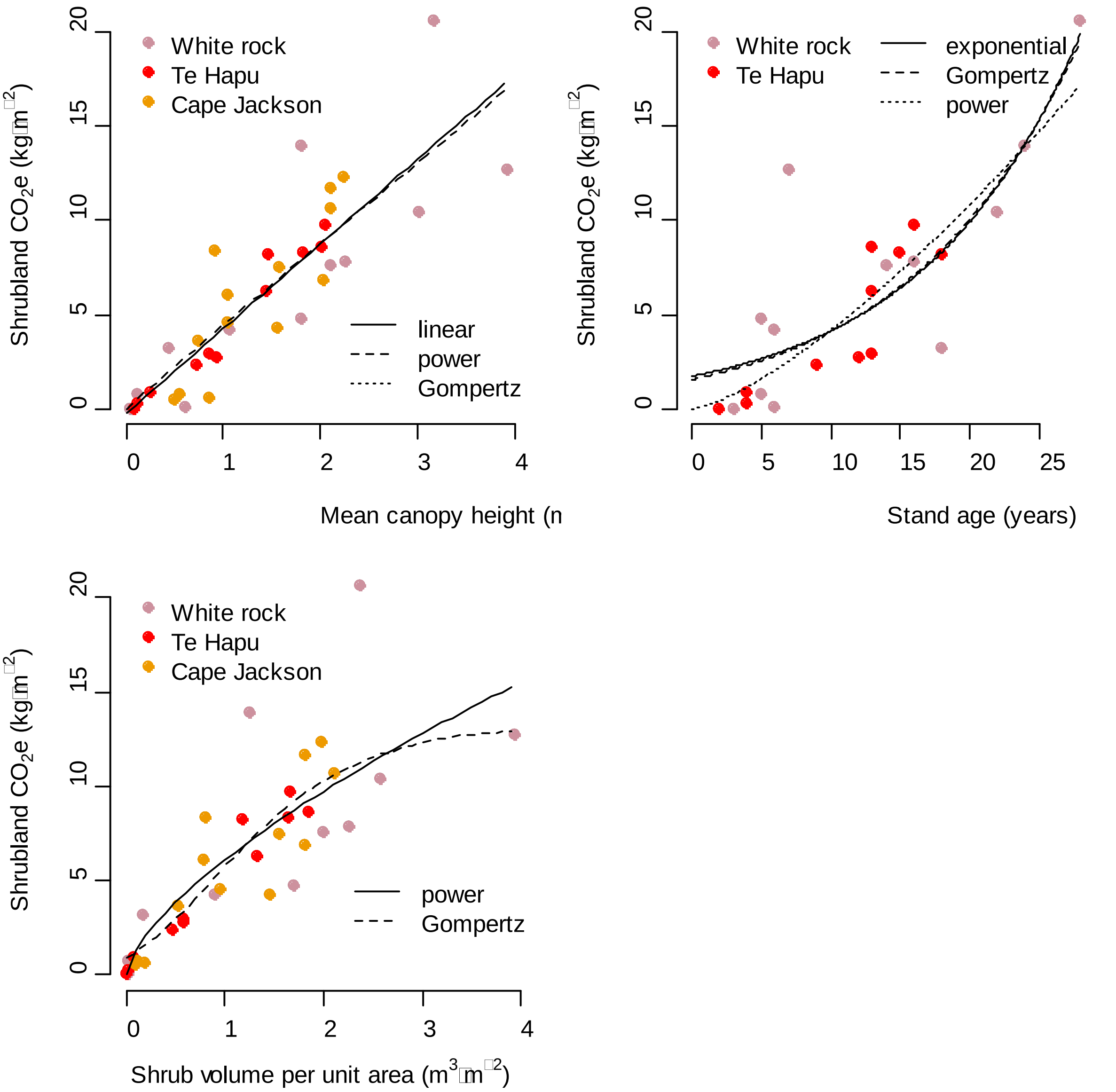


Figure 5: Tauhinu shrubland carbon (measured as CO_2 e) as a function of mean canopy height, stand age and shrubland volume. Regression lines are shown for the best supported models only.

3.2 Test of predictive value for basal diameter and stem density

When basal area and stem counts are contrasted with the other explanatory variables in two sites that had all five variables measured (Te Hapu and Turangi), we find that basal area (a function of basal diameter), volume and height have similar support as predictors of shrubland carbon and that linear and power functions are the best supported functions (Table 3). Notably, stem count was only weakly correlated with basal area ($r = -0.33$) or with mean canopy height ($r = -0.04$) and, of all tested variables, had the weakest support as a predictor of shrubland carbon (Table 3).

Table 3: Comparison of models describing allometric relationships between slope-corrected above-ground carbon (in CO_2 e kg m^{-2}) and each of five predictors measured for all plots in Te Hapu and Turangi (n = 21). Lower AICc values indicate stronger statistical support. The best supported models are emphasised in grey (within c. 2 AICc units of the lowest AICc value). The test was run on a small sample with two species and low potential for extrapolation, thus we do not provide a function for basal area.

Predictor	Model	AICc	r^2	Regr. slope
Basal area	linear	88.5	0.88	1
	power	88.8	0.87	1
	Gompertz	90.8	0.88	1
	exponential	103.1	0.74	1.01
	logarithmic	104.9	0.60	1
Height	linear	90.9	0.86	1.01
	power	91.1	0.86	1.01
	Gompertz	93.6	0.84	1.01
	logarithmic	103.1	0.66	1.01
	exponential	108.3	0.53	1
Max Age	linear	107.1	0.65	1.01
	logarithmic	107.3	0.61	1.01
	power	109	0.51	1
	exponential	110.5	0.59	1.01
	Gompertz	112	0.5	1
Stem count	power	121.8	0.1	1
	logarithmic	122	0.09	1
	exponential	122.5	0.07	1
	linear	122.6	0.06	1
	Gompertz	144.2	0.05	1
Volume	power	90.3	0.85	1
	linear	90.8	0.85	1.01
	Gompertz	94.3	0.82	1.01
	logarithmic	106.7	0.56	1
	exponential	107	0.56	1

4 Discussion

The differences in relationships between shrubland carbon and the three measures of our two shrub species (Fig. 3) indicate that more accurate predictions will result from using species-specific allometries and, where possible, it would be advantageous to develop allometries for the most common species (or architectural groups). We note that this approach differs to that currently used for trees where a single allometric relationship is used, but corrected for species-specific wood density (Beets et al. 2012), which seems appropriate given the wider variability in shrubland form or “packing”. A lower shrubland carbon for a given height or unit volume for broom compared with tauhinu corresponds with recent observations for discrete shrubs, where crown density for broom was the lowest of all species monitored within the Ministry for the Environment’s national Land Use and Carbon Analysis System (Holdaway et al. 2014). This suggests that low crown densities in discrete crowns translate into low crown densities in continuous-cover shrubland (which need not necessarily be so with shrub packing and variation across species), but a conclusive answer would require testing on other species.

Although broom has lower biomass carbon stock for a given height than tauhinu, its high carbon stocks in stands less than c. 15 years old indicate that sequestration rates are rapid during these early years. Rapid diameter and height growth in young broom stands has also been shown in early successions within montane grasslands and suggests rapid biomass increase in those situations (Bellingham 1998). On the other hand, sequestration rates saturate earlier in broom than in tauhinu, which results in tauhinu outperforming the sequestration rates of broom in stands older than c. 15 years (Fig. 3, compare also Figs 4b and 5b). The high carbon stocks recorded for old tauhinu stands (i.e. > 20 years) relied on only three plots but we also note that these stands are approximating the lifespan of tauhinu – some large tauhinu shrubs in these stands were senescent and with dying branches and would soon be overtaken by other species. As we have observed previously, it is most unlikely that the rates of sequestration of successional communities will be ever-increasing as stands become older (Carswell et al 2014), but what seems apparent from these results is that rates of sequestration are greater in tauhinu than in broom in older stands (after c. 15 years).

Our results indicate that mean height alone can provide more accurate estimates of above-ground carbon stocks than shrubland volume or stand age. The best supported-allometries were as follows:

$$\text{broom shrubland CO}_2\text{e [kg m}^2] = -0.5311 + 2.434 \times \overline{\text{H}} \quad (3)$$

$$\text{tauhinu shrubland CO}_2\text{e [kg m}^2] = -0.2228 + 4.486 \times \overline{\text{H}} \quad (4)$$

and they indicate that, on average, carbon stocks for stands of 2 m height store 43 and 87 tonnes of CO_2 e per hectare for broom and tauhinu respectively. A previous study had also found that overstorey height was a sufficiently strong predictor of above-ground total biomass for other common shrubland types in New Zealand such as gorse (*Ulex europaeus*), mānuka (*Leptospermum scoparium*) and kānuka (*Kunzea ericoides*) shrublands (Pearce et al. 2010). There was greater variability and more uncertainty in carbon–age relationships, which can result from (i) limitations in accurately estimating shrub age, (ii) more variable rates of colonisation and growth of shrubs and (iii) self-replacement in broom stands with old broom plants dying and being replaced by new ones (I.J. Payton pers. obs.). However, the carbon–age relationship is useful in that the slope of the fitted curve provides an estimate of average rates of carbon sequestration as a function of stand age (Fig. 6).

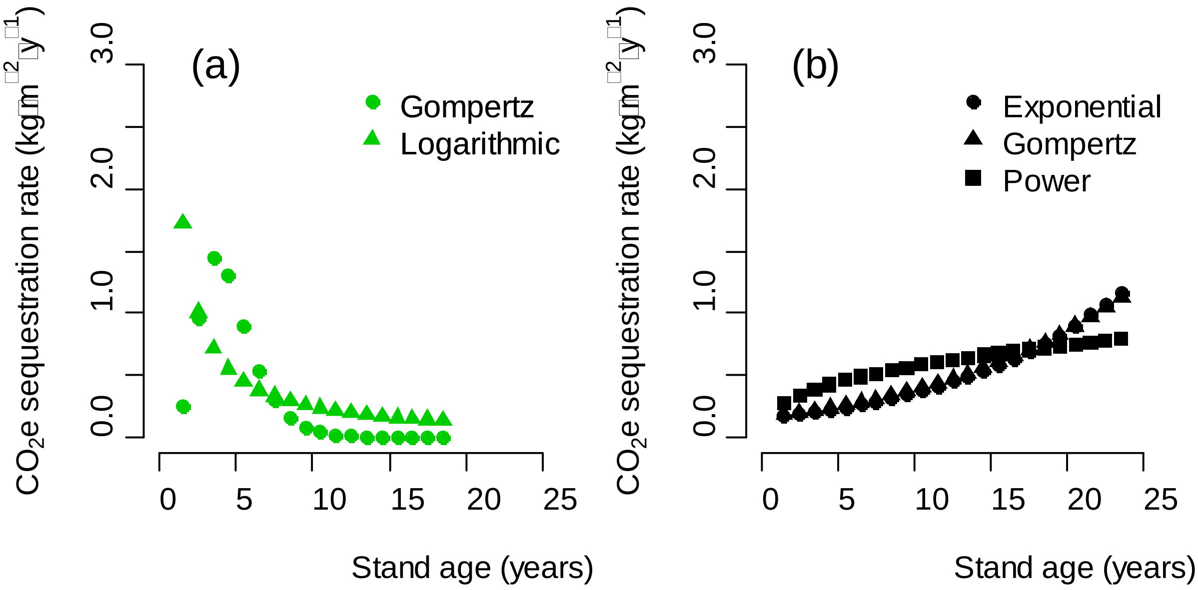


Figure 6: Mean rates of carbon sequestration for broom (a) and tauhinu shrubland (b) as a function of stand age. Rates of sequestration result from extracting the slope of the curve for the best-supported models between shrubland carbon and stand age (Figure 4b and Figure 5b) assuming that typical stands follow those main trajectories.

Other studies have found that measurements of stem basal area (or combinations of stem basal diameter and height) provide an accurate means of predicting the biomass of discrete shrubs (Conti et al. 2013; Mason et al. 2014). Our data indicate that this is also broadly the case for continuous shrubland, but that mean canopy height allows similarly accurate predictions. In practice, measurements of height are quick and efficient and require only a few minutes per plot. By comparison, measurement of basal diameters of all stems on a plot often took three people (two for measurements and one recorder) about half an hour when stem densities were high. Thus, the five-fold or greater effort required to measure basal diameters compared with heights is not justified by their similar outcomes. Another advantage of using mean canopy height as a predictor is that, in the current form, it does not require a slope correction. Any slope correction should be based on an underpinning sample that ranges across the distribution of slopes encountered to fit the allometry. This is almost never the case in practice. Given the extension and terrain of land covered by shrubland and forest, the form, magnitude and implications of slope corrections on carbon estimates is a theme that requires examination.

The low predictive power of stem counts is perhaps unsurprising if we take into account the law of constant final yield. This has been well documented for crops and some even-aged forest stands and states that, once plants fill an area of ground and start to interact with each other, standing biomass remains constant as density increases further (Weiner & Freckleton 2010). Thus, similar standing biomass can be attained either by many small stems or by few large stems and this explains the low predictive power of stem counts.

5 Conclusions and Recommendations

- Mean canopy height can be used to accurately predict carbon stocks both in broom and tauhinu. We note that mean canopy height should be measured systematically. We suggest taking nine height measurements within a 4 × 4 m plot in continuous shrubland and 17 height measurements within a 4 × 4 m plot where shrubs occur as discrete clumps (the first nine measurements can be taken on all internal intersections of a 1 × 1m grid overlaid on the plot and the additional ones every 2 m along the plot perimeter).
- Predictions that rely on basal area or shrubland volume are similarly accurate to those based on mean shrub height, such that the additional work required to measure them is not justified by greater accuracy.
- The relationship between carbon and stand age is inherently more variable than that with mean height but this relationship has the advantage of allowing estimation of sequestration rates as a function of stand age.
- We provide equations to predict above-ground shrubland carbon and broom and tauhinu as a function of mean canopy height and stand age (Table 2). Predictions will be more reliable when applied within the range of values used to calibrate the equation for each predictor (less than 4 m mean height and 20 year-old stands for broom and less than 3.5 m height and 25 year old stands for tauhinu). On average, carbon stocks for stands with mean height of 2 m store 43 tonnes of CO_2 e per hectare for broom and 87 tonnes of CO_2 e per hectare for tauhinu.
- Differences between species are clear and justify developing specific allometries for main shrubland types. Broom typically produces canopies with low carbon density but sequesters carbon rapidly when stands are young. Tauhinu canopies have greater carbon density and appear to increase sequestration rates in later successional stages. For cases where a species-specific allometry is not available, we suggest that a ‘mean shrub allometry’ be developed using hierarchical models (Gelman and Hill 2007) and all existing continuous shrubland harvest data.

6 Acknowledgements

This project was supported by Ministry for Primary Industries Sustainable Land Management and Climate Change (SLMACC) funding (contract LCR131411). We thank landowners John Shrimpton (Glenthorne), Mike Macfarlane (Hawkswood), the Hore family (Nokomai Station), Ron Marriott (Cape Jackson) and Mr and Mrs Reuter (Dyers Pass) for providing access to their land and for allowing destructive harvest of their shrublands. Robert Durling (Athol Volunteer Rural Fire Force), Mike Grant (Southern Rural Fire Authority, Invercargill), and Hamish Neal helped to identify sites in Nokomai; Dave Lumley (DOC Tongariro District Office, Whakapapa) enabled access to public land in Turangi. We also thank Kathrin Affeld, Veronica Clifford, Kev Drew, Lydia Hale, Dave Henley, Jess Kerr, Brooke O'Connor, Graeme Rogers and Mark West for assisting with recent fieldwork. In addition, Rowan Buxton, Fabien Dangeron, Alice Miller and Graeme Rogers assisted with field-work at Dyers Pass, and Melissa Brignall-Theyer, Stewart MacKenzie and Jenny Burrows contributed with field measurements at Cape Jackson. The report benefitted from perceptive observations made by Ian Payton and careful editing by Christine Bezar.

7 References

Bascand LD, Jowett GH (1982) Scrubweed cover of South Island agricultural and pastoral land 2. Plant distribution and managerial problem status. New Zealand Journal of Experimental Agriculture 10: 455-92.

Beets PN, Burrows L, Buxton R, Carswell F, Dangeron F, Oliver GR, Kimberley MO, Pearce S, Pearce G, Robertson K, Rogers G, Wiser S. (2001) Task B1 and B2: Allometric functions for native forest trees and shrubland. Landcare Research Report JNT0001/133, prepared for Ministry for the Environment.

Beets PN, Kimberley MO, Oliver GR, Pearce SH, Graham JD, Brandon A (2012) Allometric equations for estimating carbon stocks in natural forest in New Zealand. Forests 3: 818-839.

Bellingham PJ (1998) Shrub succession and invasibility in a New Zealand montane grassland. Australian Journal of Ecology 23: 562-573.

Bolker, BM (2008) Ecological models and data in R. Princeton University Press.

Burrows L, Cieraad E, Head N (2015) Scotch broom facilitates indigenous tree and shrub germination and establishment in dryland New Zealand. New Zealand Journal of Ecology 39: 61-70.

Carswell F, Brignall-Theyer M, Burrows L, McKenzie S (2006). An allometric relationship between shrub volume and Carbon for Tauhinu (*Ozothamnus leptophyllus*). Landcare Research Internal Report: LC0506/146. 43 p.

Carswell F, Burrows L, Easdale T, Mason N, Holdaway R, Payton I, Fraser A, Karl B, Grant Pearce G (2014) Tools to predict carbon sequestration in regenerating shrublands. Landcare Research Contract Report LC1899 for the Ministry for Primary Industries, Wellington.

Conti G, Enrico L, Casanoves F, Diaz S (2013) Shrub biomass estimation in the semiarid Chaco forest: a contribution to the quantification of an underrated carbon stock. Annals of Forest Science 70: 515-524.

Gelman A, Hill J (2007) Data analysis using regression and multilevel/hierarchical models. CUP, New York.

Holdaway RJ, Easdale TA, Mason, NWH, Carswell FE (2014) LUCAS Natural Forest Carbon Analysis. Prepared for the Ministry for the Environment by Landcare Research. Wellington: Ministry for the Environment. LC2010.

Mason NWH, Beets PN, Payton I, Burrows L, Holdaway RJ, Carswell FE (2014) Individual-based allometric equations accurately measure carbon storage and sequestration in shrublands. Forests 5: 309-324.

Ministry for Primary Industries (2012) A guide to the Field Measurement Approach for Forestry in the Emissions Trading Scheme. http://www.mpi.govt.nz/document-vault/3666

Payton IJ, Forrester G, Lambie S, Berben P, Pinkney T (2009) Development and validation of allometric equations for carbon inventory of indigenous forests and shrubland. Landcare Research Contract Report LC0910/004, prepared for the Ministry of Agriculture and Forestry, Wellington, New Zealand. 64p.

Pearce HG, Anderson WR, Fogarty LG, Todoroki CL, Anderson SAJ (2010) Linear mixed-effects models for estimating biomass and fuel loads in shrublands. Canadian Journal of Forest Research 40: 2015-2026.

R Development Core Team (2009) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Trotter C, Tate K, Scott N, Townsend J, Wilde H, Lambie S, Marden M, Pinkney T (2005) Afforestation/reforestation of New Zealand marginal pasture lands by indigenous shrublands: The potential for Kyoto forest sinks. Annals of Forest Science 62: 865-871.

Weiner J, Freckleton RP (2010) Constant Final Yield. Annual Review of Ecology, Evolution, and Systematics 41: 173-192.

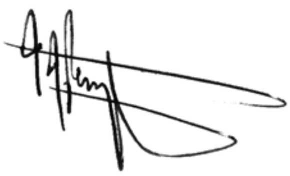
Review of Easdale et al. (2015) Improved allometric functions for scotch broom and tauhinu

I have read through the report and made notes in tracked changes concerning points I would like the authors to think about. In addition I would make the following comments:

1. I am very pleased to see the testing of multiple predictors (height, volume, age) and models (linear, power, Gompertz, exponential, logarithmic) so we can see the relative merits of the different options.
2. The conclusion is that height is the best predictor of carbon stocks in these shrubland types. While height is the parameter that is measured, the measurements are taken for a fixed area – i.e. average height per square metre. So in effect you're measuring a volume. We go to some lengths to carefully define the on-ground area of the plot and to slope-correct it. I'd like to see (not necessarily in this study) an assessment of the effect of the number of height measurements on mean stand height and therefore on the carbon stock estimate.
3. Stand age. From my efforts to age broom stands during a previous SLMACC project, I concluded that the age of the largest stems is only a good indicator of the age of the stand in the early years of stand development. Broom is a relatively short-lived plant. As stands age the older plants die and are replaced by new broom bushes. Thus broom can have been present at a site for many years, but the age of the largest stems will not reflect that.
4. The discussion section opens with a statement that "where possible for common species, allometries need to be species specific." I don't necessarily disagree with that, but I find it interesting that for tree species in natural (as opposed to planted) forests "we" argue the opposite case – i.e. a single allometric equation that uses a wood density parameter to account for species-specific differences.
5. In earlier reports written to support the development of New Zealand's carbon accounting methodologies we typically argued that the allometries that were developed were the best we could achieve with the data that were available. The present report raises two questions for me.
    - How much of an improvement are the new allometries over those we had previously?
    - Have we done enough, and if not what more could/should be done to make these allometries better fit-for-purpose?
6. One further thought. I'd have liked to see a map showing the distribution of the species and the distribution of the study sites.

Conclusion

This is a well presented report by a competent group of researchers. I have enjoyed reviewing it.



Ian Payton

In addition to the above, we transcribe the main additional comments given as tracked changes on the draft report:

7. Need to specify how you did your slope measurements, and state that all estimates used in the analysis are based on slope-corrected data.

8. For stand age you measure wet age and lab age, but only use lab age. Suggest you state in the methods section how you determine stand age, and then in the results section just refer to stand age. Ie. Use stand age rather than lab age.

9. Not clear how you use the basal diameter data. Is this converted to basal area? When most people read basal area, they're going to think of dbh.

10. Does tauhinu get much older than 20 years?

11. "the carbon - age relationship is useful in that the curve can be decomposed to estimate average rates of carbon sequestration as a function of stand age". What does this mean???

Authors' response to the review

We thank Ian Payton for his constructive review. By asking to clarify or expand on some points, his input helped to improve the technical quality of the report. We explain our response point by point:

2 – We agree with the observation that mean canopy height is in effect a measure of crown volume. We now make a recommendation that at least nine height measurements should be taken for continuous shrubland within a 4 × 4 m plot and that 17 height measurements should be taken within a 4 × 4 m plot where shrubs occur as discrete clumps. We are confident that these will provide sound estimates of mean canopy height.

3 – A most fitting observation. We now list stand self-replacement as another source of noise in age estimations for broom stands (page 15) and quote the observation.

4 – We edited the text to indicate that species-specific allometries would be required only for common shrub species where possible and make it explicit that this recommendation differs from a previous recommendation made for trees. We also suggest to develop a 'mean shrub allometry' with all existing continuous shrubland harvest data that can be used where a species-specific allometry is not available.

5- Regarding further developments, we now suggest in page 16 that slope correction procedures can be affecting the accuracy of carbon accounting and require examination.

6- We produced a map with site locations. Species distribution maps are available from DOC's weed database and from Bascand and Jowett (1982) but IP rights limit us from reproducing them.

7- In page 6 we explain how and why we measured average slope angle in each plot. We also revised the analysis so that basal area and stem counts are now also slope corrected. This did not affect our interpretation of results.

8- We now explain that we relied on lab-based estimates of stand age and standardized the terminology throughout.

9- Page 8 now includes a brief explanation of how we measured basal area.

10- Good point. We discuss this in the second paragraph of page 15. The large plants in old tauhinu stands look senescent and seem to be approaching their lifespan but we cannot confirm that this is also the case for the stands if tauhinu self-replaces in a similar way that broom does.

11- We now explain that the slope of the models for carbon stock as a function of stand age (Fig 6) represents a rate of sequestration (page 15).