Additional web material: Evaluation of volume functions and patterns of growth in *Eucalyptus gunnii* in the UK.

Introduction

Growth of *E. gunnii* in the UK has been estimated in a small number of studies [1,2], but a complicating factor is the lack of functions to relate DBH and height to volume for trees grown in the UK. Volume functions for *Eucalyptus gunnii* are available for trees grown in France in the mid Pyrenees [3] and these have been used to estimate tree volumes in the UK [1,2]. A general volume function for cold tolerant eucalypts developed in Chile [4] has also been used to calculate volumes [2]. Other approaches taken to calculating tree volumes of *E. gunnii* in the UK include the use of the tariff system, as described in Matthews and Mackie [5], which is commonly used for estimating standing timber volumes in the UK. This was applied to *E. gunnii* diameter and height data with certain assumptions on stem form [1]. It is likely that the French volume function, given it is based on measurements of *E. gunnii,* estimates volumes of trees grown in the UK with reasonable precision and this assumption was tested in this study.

The pattern of growth are not understood for stands of *E. gunnii* in the UK and characterising this is problematic due to a lack of time-series data. As such, trees have been destructively sampled from stands in a northern (Glenbranter) and a southern stand (Chiddingfold) and stem analysis employed to investigate when current annual increment (CAI) and mean annual increment (MAI) peak.

There were therefore two main objectives of this study:

1. To evaluate the precision of available volume functions, relating height and DBH to stem volume when applied to *E. gunnii*.
2. To investigate patterns of growth in two sites, one in the south and one in the north of Great Britain.

The approach adopted and results of these studies are described in the following sections.

Methods and analysis

Study 1: Validation of volume functions

During 2011 and 2012 stem volume data were collected from trees of ages ranging from 6 years to 43 years, and from southern, central and northern areas of the UK (Figure 1) to test the applicability of the AFOCEL [3] and Shell [4] volume functions to trees in the UK. These data were collected using three techniques; from trees felled for stem analysis, from trees where taper was measured using a Lazer Technology Inc. Criterion RD1000 optical dendrometer and from trees that were scanned using a Leica Terrestrial Laser Scanner (TLS) and their volumes estimated using a programme devised by Dr Eric Casella at Forest Research. The number of trees, their age, the method used to measure volume and their locations are shown in Table 1 and Figure 1.

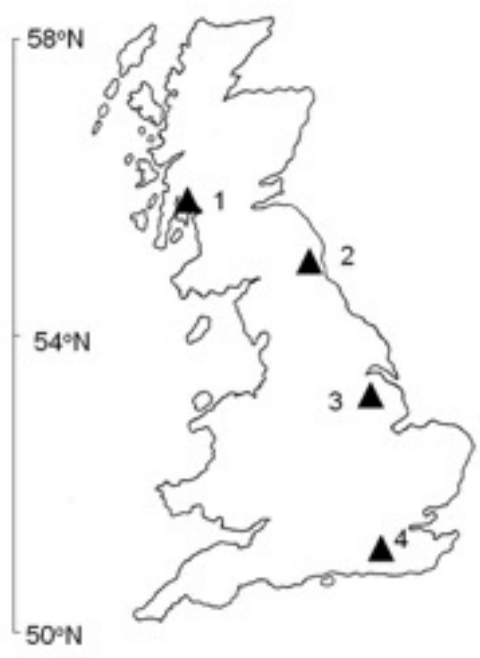

Figure 1. Location of sites for tree volume data collection (1=Glenbranter, 2=Woodhorn, 3=Thoresby, 4=Chiddingfold).

For the optical dendrometer, measurements of diameter and height were taken at one tenth height increments up the stem from the base, the number being dictated by the length that could be easily viewed up the stem before it was obscured by the crown. These varied from 5 to 8 measurements. A separate study of *E. nitens* stem form and volume (unpublished results) showed that the stem volumes estimated from 5 to 8 optically measured diameters and the full ten diameters from felled trees were not statistically significantly different from each other ($p>0.05$).

Table 1. Location, number, age of trees and measurement method for trees used in the stem

form study.

Location	Latitude, Longitude	Number of trees	Age (years)	Method
Woodhorn	55°11'17"N, 1°32'35"W	473	6	Terrestrial laser scanner
Thoresby	53°26'32"N, 0°59'39"W	25	10	Optical dendrometer
Chiddingfold	51° 03' 49"N, 0° 35' 19"W	10	27	Trees felled for stem analysis
Glenbranter	56°07'38"N, 5°03'16"W	2	43	Trees felled for stem analysis

Stem volumes were calculated by summing the volumes calculated for each section. The volume for each section was estimated using Smalian's formula [6], for all sections except the top of the tree, where the equation for a cone was used [6]. The equation for Smalian's formula is shown below, followed by the equation for the volume of a cone:

Smalian's volume = $L(\pi \bullet d_1^2 + \pi \bullet d_2^2)/8$

Volume of a cone = $(\pi \bullet d_2^2 \bullet h)/12$

Where L is length of section, d_1 is the diameter at the top of the stem section and d_2 is the diameter at the bottom of the stem section.

The volumes calculated were compared to the tree overbark stem volumes estimated using the AFOCEL volume equation [3] and Shell function [4]. The AFOCEL equation incorporated height and diameter at breast height, where V= overbark stem volume (m^3), DBH = diameter at breast height (cm) and h=height (m).

$$V=(-5.04+(0.03556 \bullet DBH^2 \bullet h))/1000$$

The Shell function was developed for cold tolerant eucalypts in general and is not specific to *E. gunnii*. This assumes a form factor of 0.35 giving a formula for overbark stem volume of:

$$V=0.35(\pi \bullet DBH^2 \bullet h))/40000$$

The accuracy of the Shell and AFOCEL functions was compared by calculating a value for the residual (R), the percentage difference between measured stem volume (V_m) and calculated stem volume (V_c) using this equation:

$$R = (100 \bullet (V_m - V_c))/V_m$$

These were plotted against tree stem volume to examine bias in the application of each equation. To estimate biomass, stem volume was converted to stem biomass using a bulk density of 1050 kg m^{-3} and a dry weight density of 500 kg m^{-3} [7].

Study 2: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

To provide continuous growth data for *E. gunnii* trees, ten trees were felled at Chiddingfold and two at Glenbranter (Figure 1) and growth assessed using stem analysis. Table 2 describes the two sites. Stem analysis is a well-established technique in tree growth studies and has been used previously for analysing growth in eucalypts (eg [9]).

For the trees at Chiddingfold, ten discs were cut at the base, DBH and at nine equidistant points up the stem up the stem, while for Glenbranter trees five discs were cut. These were scanned at 1,200 dpi at a 100% scale using an Epson Expression 1,000 A3 flatbed scanner to produce detailed scans of the discs. Regent Instruments Windendro 2004 tree ring analysis software was used to measure annual ring widths across eight radii evenly distributed around the discs. The mean annual ring width across these eight radii was used to calculate volume in a Microsoft Excel spreadsheet. A Prior binocular microscope at 10x magnification was used to help determine the boundaries of some of the narrower rings on the discs. The number of discs and radii sampled provided a precise estimate of volume growth. Newton [9] in an assessment of sampling strategies for estimating volume growth, determined that ten to eleven equidistant sections of the stem and four radii based on the smallest and largest diameters provided data that is precise.

Table 2. Site description and climate variables for Glenbranter and Chiddingfold generated by ESC [10]. AT5 = accumulated temperature above 5°C, CT = continentality, DAMS = Detailed Aspect Method of Scoring and MD = moisture deficit.

Location	Glenbranter	Chiddingfold, Plaistow
Elevation/ Aspect	250m/ south east	60m/ south west
Exposure	Open to south east	Open to most directions
Slope	South east	Gentle to south west
Geological formation/ soil	Morainic drift/ brown earth	Weald clay/ clay
AT5	1331.1	1935.1
CT	4.4	10.2
DAMS	12.3	11.4
MD	106.3	209.7
Summer Rainfall (mm)	991.1	351.2
Winter Rainfall (mm)	1522.3	463.8

Volume growth was estimated by identifying height at each age and cross sectional area at each age. Height attained at each age was estimated at ten (Chiddingfold) or five (Glenbranter) points up the stem using the age minus the number of rings on the disc at that section. Height for the final year's growth in each section was modified by applying Carmean's formula, identified by Dyer and Bailey [11] as most precisely estimating length of the final year's "hidden tip" in the stem sections. Annual height growth within stem sections was calculated by dividing the length of the sections by the number of years' growth in that section. A curve was fitted to the height data by age using the best fitting (based on high R^2 and low standard error of the estimate) using SPSS v19. The equations used to fit height data to age (12,13) are shown below:

1. Gompertz model: $y = a \bullet \exp(-\exp(b^{-cx}))$
2. Exponential model: $y=a \bullet \exp(b(x+c))$
3. Richard's model: $y=a \bullet (1-\exp(b \bullet x)^{c})$
4. Korf model: $Y=a \bullet (\exp(b \bullet x^{-c})$

Where y is height and x is age in years, with a, b and c being parameters in the models.

To determine annual cross sectional area growth, ring widths obtained through Windendro from the scans of the discs were converted to cross sectional areas. Volumes for each year were then calculated by applying Smalian's formula to the cross sectional area attained at the end of that year multiplied by the section length. Where annual growth ended in the stem section the volume was calculated by using the equation for the volume of a cone applied to the cross sectional area and the estimated height at which growth stopped for that year. For each year the volume growth in all sections was added together to obtain growth for that year, the CAI. MAI was calculated by dividing the total volume by the age. The stem analysis therefore provided CAI, MAI and cumulative volume production for each tree.

For the trees at Chiddingfold the crown projection was also calculated by measuring distances from stem to canopy edge and bearings at eight points using a method developed by Forest Research [14]. The first step in this method was to mark out the projection (area) of the crown by defining its extent as precisely as possible using eight marker posts. The distance and bearing from magnetic north to these posts was then measured using a tape and Suunto KB-14 compass respectively. In calculating distance from the tree stem to the canopy edge, half of the stem diameter was added in as the measurement was taken from the stem surface, not stem cross sectional mid point. The area of the crown projection was calculated by summing the area of the eight triangles, each defined by the tree stem and two marker posts. The following equation was used to calculate the area of each triangle:

$A = \sin \alpha(a \bullet b)/2$

Where a is the distance to one pole, b is the distance to another and α is the angle between the two poles.

To convert each tree's growth into a per hectare basis, the crown projection (m^2) was used to determine an appropriate stocking per hectare. This was undertaken using the following equation:

Stocking = 10,000/ crown projection

For the two trees at Glenbranter stocking was estimated at 871 ha^{-1}, based on stocking of trees in seven 0.01 ha plots measured when TLS measurements were taken.

The tree MAI, CAI and cumulative volumes of the individual trees were multiplied by the stocking to convert growth and volume to a per hectare basis. Curves were then fitted using the curve fitting function in SPSS v19 using the data directly or where applicable asking a natural logarithm. Functions were selected on the basis of high R^2, low standard error and a visual assessment of fit.

3.0 Results

3.1 Study 1: Validation of volume functions

The data for DBH, height and stem volume were divided into three groups; the six year old trees from Woodhorn (n=473), the ten year old trees from Thoresby (n=25) and the combined 27 and 43 year old trees from Chiddingfold and Glenbranter (n=12).

The median residual of estimated tree volume against actual tree volume was calculated and plotted against stem volume. In general the AFOCEL function provided a better fit (Table 3), but for very small trees present on the Woodhorn site, it was clear that the AFOCEL function was not appropriate; estimated volume for small trees being negative. However if trees below 10cm DBH were excluded the AFOCEL function also provided a better fit for tree volumes at Woodhorn. The Shell function consistently underestimated tree volume in all cases. The residuals plotted against tree volume are shown in Figures 2 to 4.

Table 3. Median residuals for Shell and AFOCEL functions. [a] Function produces negative volume values for small trees.

	Shell function	AFOCEL function
Woodhorn (all trees, n=473)	26.4%	34.4%[a]

Woodhorn (trees DBH>10cm, n=126)	20.5%	9.1%
Thoresby	14.1%	-4.4%
Chiddingfold/ Glenbranter	22.6%	1.2%

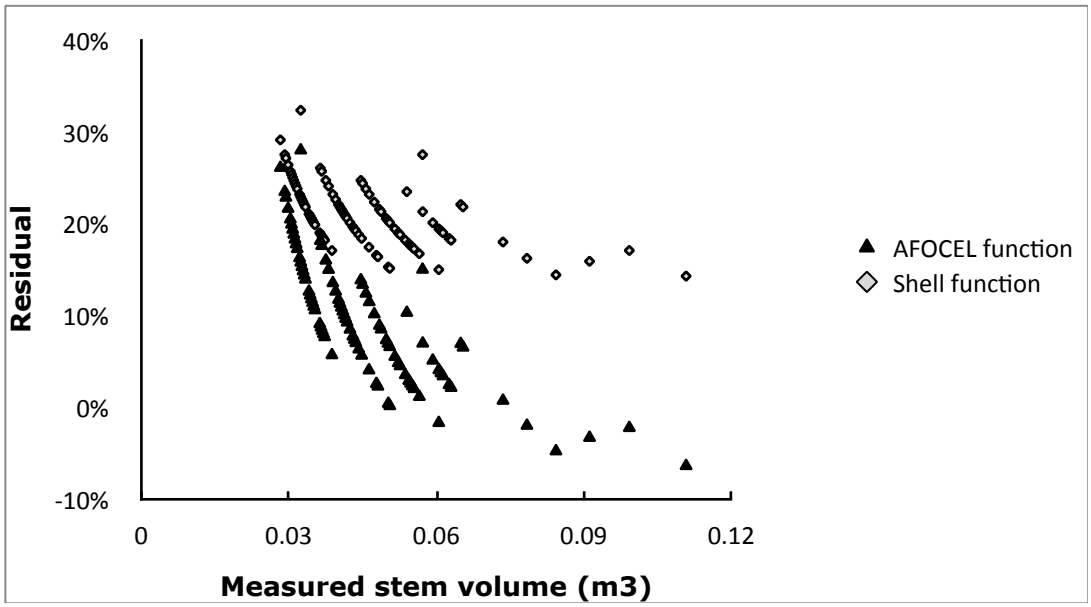

Figure 2. Residuals for AFOCEL and Shell functions against stem volume for Woodhorn

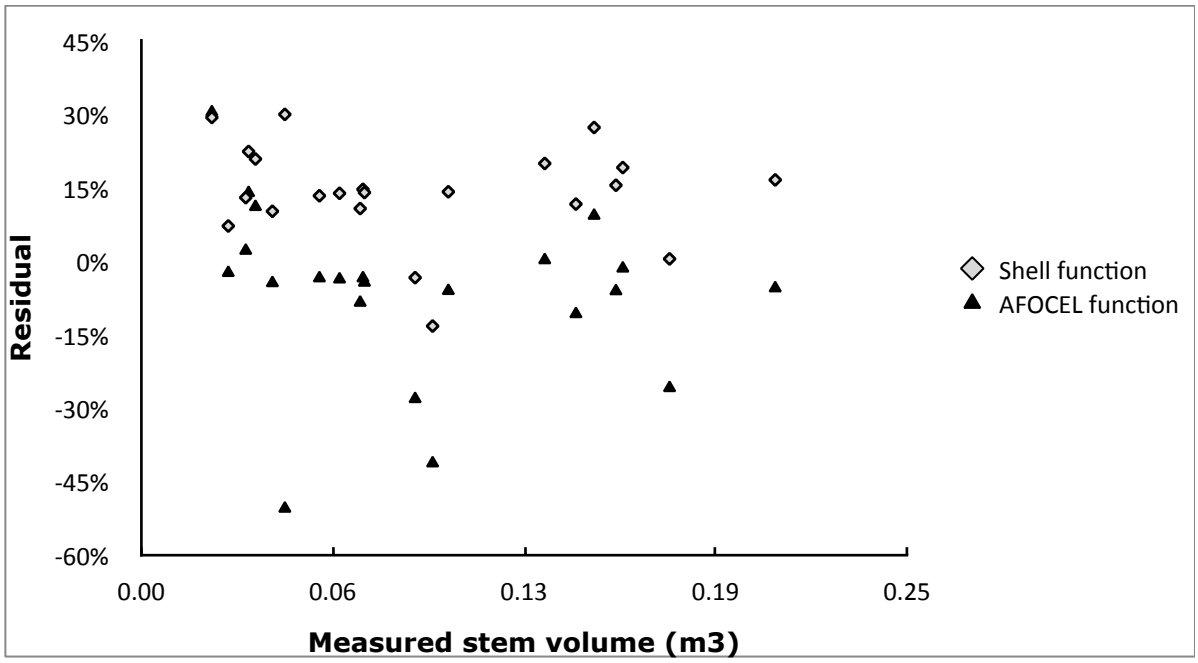

Figure 3. Residuals for AFOCEL and Shell functions against stem volume for Thoresby.

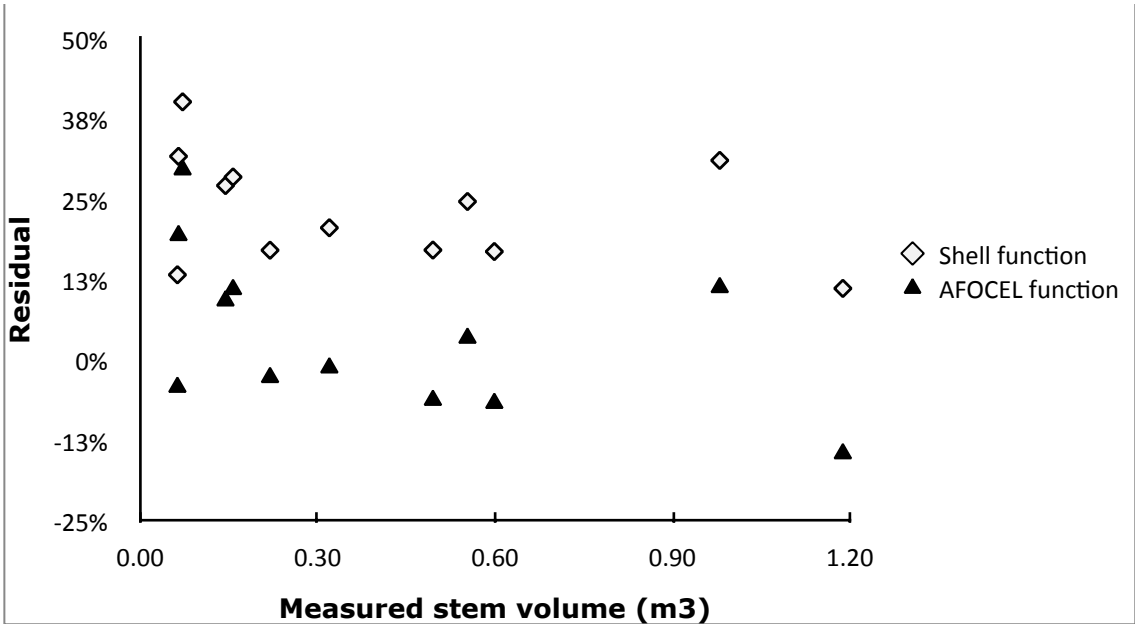

Figure 4. Residuals for AFOCEL and Shell functions against stem volume for Chiddingfold/ Glenbranter.

3.2 Study 2: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

One tree of the ten from Chiddingfold was excluded from the stem analysis, as the age determined from ring counts was much less than that of the known age of 28 years. Possible reasons for this are commented upon in the discussion. A summary of dimensions and growth variables for each of the ten trees is shown in Table 4.

Table 4. Growth variables at 28 years of age for the trees at Chiddingfold.

	Tree number									
	1	2	3	4	5	6	7	8	9	10
DBH (cm)	36.2	10.6	19.7	15.4	11.6/ 9.6	11.2	25.4	11.9	1.7/ 9.9	26.8
Height (m)	29.3	14.3	23.8	16.1	18.0	15.8	23.5	11.0	17.2	25.2
Volume (m^3) ob	1.127	0.047	0.283	0.115	0.157	0.062	0.380	0.071	0.214	0.483
Volume (m^3) ub	1.062	0.044	0.271	0.108	0.148	0.056	0.363	0.067	0.199	0.464

MAI (m^3 ha^{-1} y^{-1}) ob	16.3	5.8	9.3	1.9		4.0	5.7	3.2	7.6	4.8
CAI (m^3 ha^{-1} y^{-1}) ob	27.2	5.4	10.3	1.9		2.6	3.6	3.3	6.7	4.3
Crown Projection (m^2)	23.25	2.75	10.46	20.07	11.24	5.02	22.79	7.61	9.34	34.84
Effective stocking (number ha^{-1})	430	3632	955	498	893	1991	431	1313	1071	287
Volume (m^3 ha^{-1}) ob	457	161	259	54	140	11	159	89	213	133

Figure 5 shows height by age and the best fitting relationship was a Richard's function having highest R^2 and lowest SEE (Table 5). For most ages, height was found to be normally distributed so means and error bars are also shown in Figure 5 for ages where there were sufficient data. The relationship between DBH and height for trees at Chiddingfold is shown in Figure 6 and the equation for the best fit curve based on high R^2 and low SEE in Table 5.

Shapiro-Wilkes tests showed that the distribution of MAI and cumulative volumes by age of the nine trees was significantly different from normal at some ages and so median values for MAI and cumulative volume were used to generate growth curves on a tree and per hectare basis. Figure 7 illustrates the range across the nine trees for cumulative volume production per tree (m^3) and the median, while Figure 8 shows the range and median on a per hectare basis. The median CAI and MAI by age is shown in Figure 9.

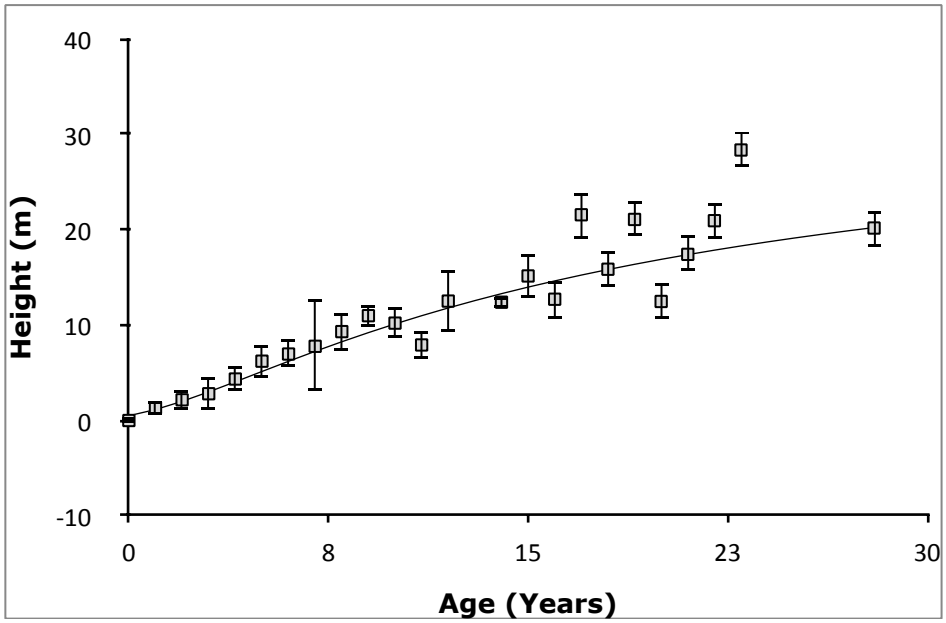

Figure 5. Height by age from stem analysis of Chiddingfold trees, with mean height and standard error of the mean.

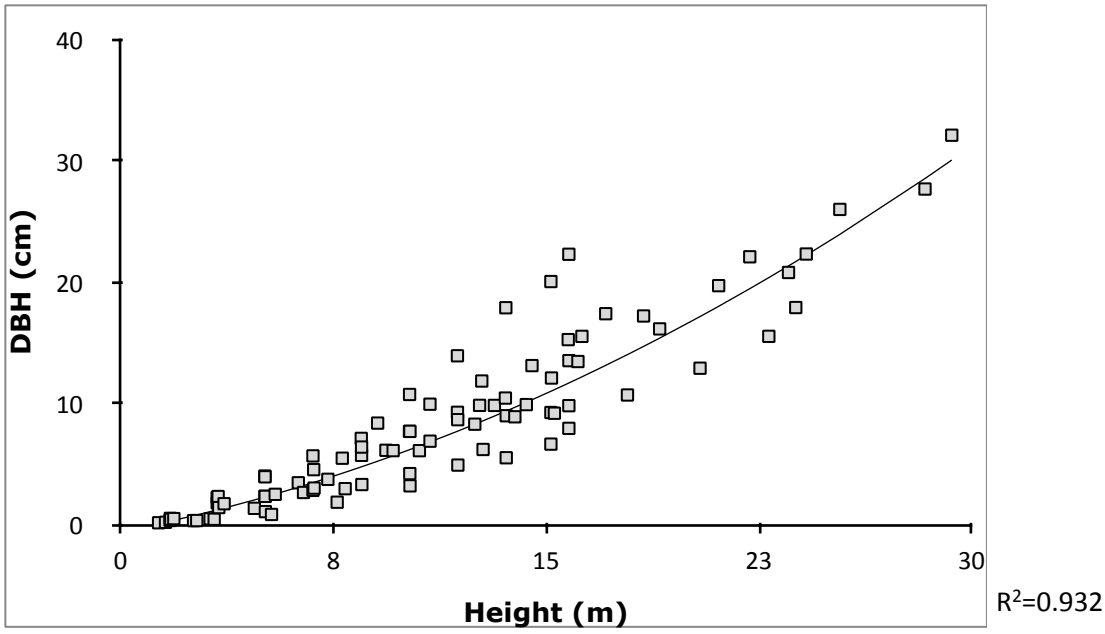

Figure 6. DBH by height of Chiddingfold stem analysis trees, with best fit curve.

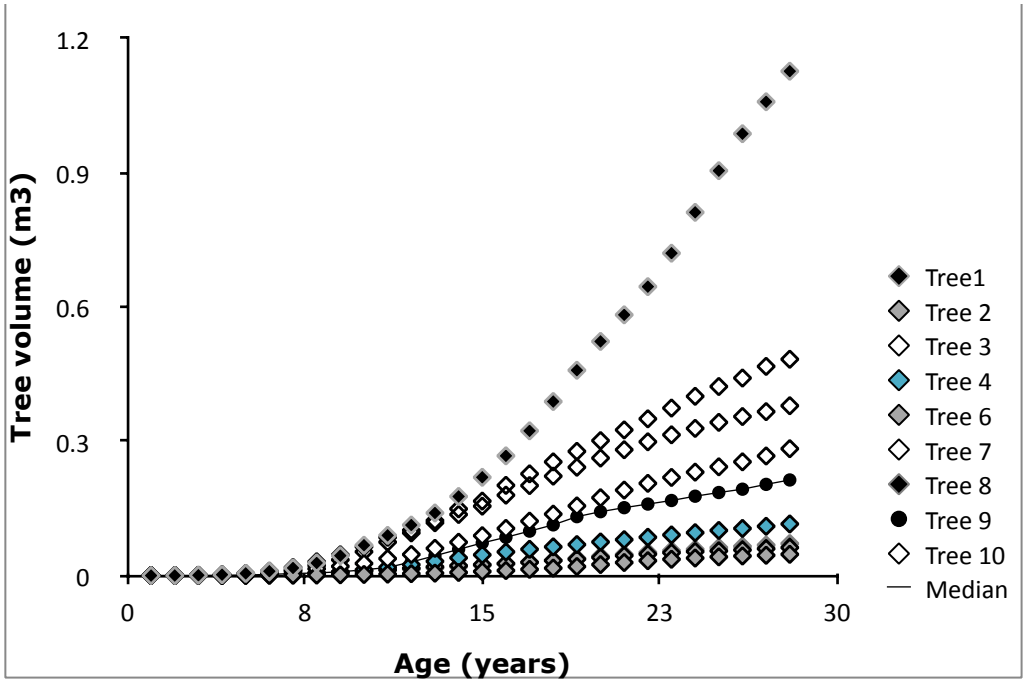

Figure 7. Overbark volume for each tree and the median by age at Chiddingfold

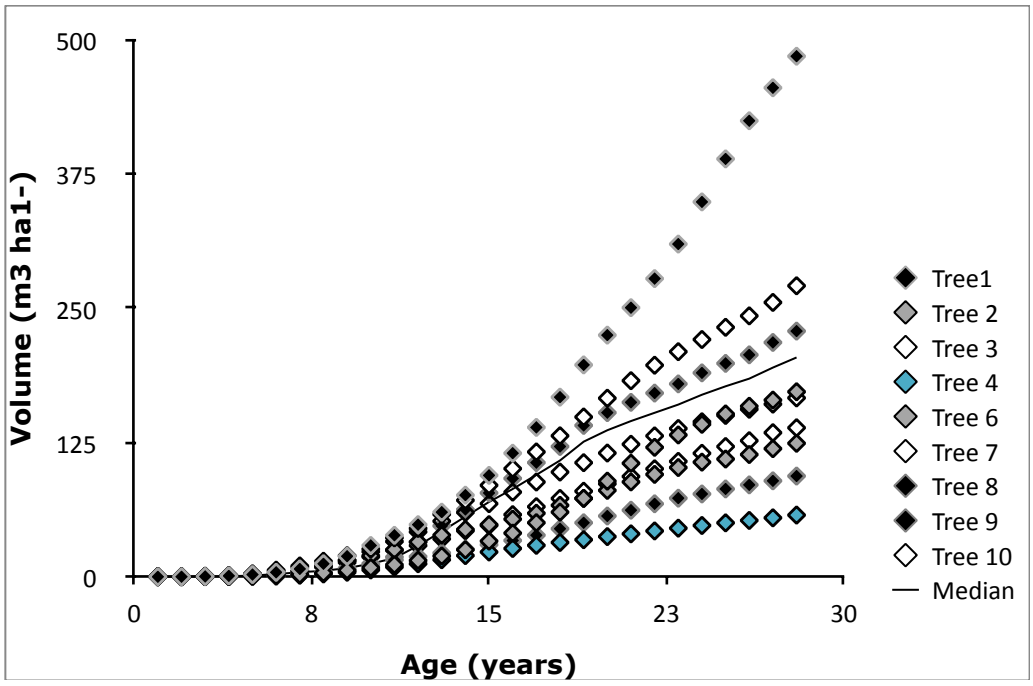

Figure 8. Overbark volume per hectare and the median by age at Chiddingfold.

The curves fitted to the age and cumulative volume and age and MAI on an overbark and underbark basis are shown in Table 5, the best fit curve being selected on the basis of high R^2 and low SEE.

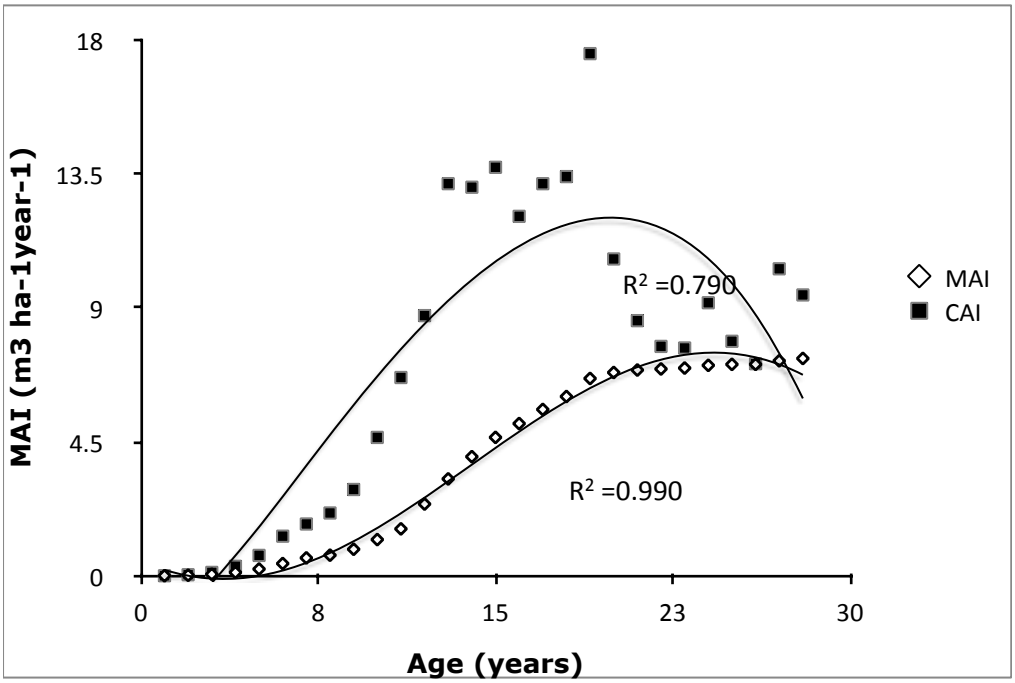

Figure 9. Mean annual increment (MAI) and current annual increment (CAI) (overbark) by age of the median tree at Chiddingfold.

Table 5. Description of best fit models relating growth variables to age for median Chiddingfold tree.

X	y	Model	N	R^2	SEE	a	B	c	d
Age (years)	Height (m)	Richards	99	0.762	3.392	30.051	-0.062	0.66	
Height (m)	DBH (cm)	$y= ax^2+bx+c$	91	0.932	1.884	0.02	0.46	-0.614	
Age (years)	Volume (m^3ha^{-1}) ob	$y=ax^3+bx^2+cx+d$	28	0.997	5.070	-0.25	1.299	-10.493	17.690
Age (years)	MAI ($m^3ha^{-1}y^{-1}$) ob	$y=ax^3+bx^2+cx+d$	28	0.990	0.770	-0.002	0.067	-0.398	0.544
Age (years)	Volume (m^3ha^{-1}) ub	$y=ax^3+bx^2+cx+d$	28	0.996	4.651	-0.024	1.254	-10.240	17.427
Age (years)	MAI ($m^3ha^{-1}y^{-1}$) ub	$y=ax^3+bx^2+cx+d$	28	0.991	0.284	-0.002	0.065	-0.390	0.528

Volume and MAI curves are fitted for data at ages 5 years and above, except for volume underbark which was for data at ages 6 years and above.

A similar approach was taken for developing growth curves for the two trees felled at Glenbranter. The relationship between height and age was best described, based on high R^2 and low SEE by a Richards function (Table 6). For DBH and height, the best fitting function based on highest R^2 and low SEE was a polynomial one which is described in Table 6. Table 6 also describes the best fit models relating growth variables to age or height for Glenbranter trees. When fitting the curves three provided a particularly good fit based on R^2 and SEE; cubic, quadratic and power functions. However the quadratic one gave negative values of volume between age 5 and 18 years. The power one was a poorer fit at older ages of greater than 30 years. The cubic function has none of these shortcomings and so has been selected.

Table 6. Description of best fit models relating growth variables to age or height for Glenbranter trees.

X	**y**	**Model**	**N**	**R^2**	**SEE**	**a**	**B**	**c**	**d**
Age (years)	Height (m)	Richards	86	0.995	0.558	37.007	0.027	1.101	
Height (m)	DBH (cm)	$y=ax^3+bx^2+cx+d$	85	0.984	1.028	0.003	0.068	0.815	-1.290
Age (years)	Volume (m^3 ha^{-1}) ob	$y=ax^3+bx^2+cx+d$	43	0.994	12.470	0.013	-0.345	3.190	-6.224
Age (years)	MAI (m^3 ha^{-1} y^{-1}) ob	$y=ax^3+bx^2+cx+d$	43	0.992	0.338	0.00016	-0.00034	0.00708	0.0581
Age (years)	Volume (m^3 ha^{-1}) ub	$y=ax^3+bx^2+cx+d$	43	0.993	11.853	0.012	-0.327	2.934	-5.678
Age (years)	MAI (m^3 ha^{-1} y^{-1}) ub	$y=ax+bx^2+cx+d$	43	0.992	0.321	0.00015	-0.00018	0.00147	0.0583

4.0 Discussion

4.1 Study 1: Validation of volume functions

For trees of dimensions likely to be used for biomass, the AFOCEL volume function estimated volume of *E. gunnii* more precisely than the Shell function. This was predictable, as the function was developed using data from stands of *E. gunnii* and *E. x gundal* hybrids in France [3], whereas the Shell function was a more general equation covering a range of commercial cold tolerant eucalypts in Chile [4], which were unlikely to include *E. gunnii*.

The residuals for estimates of stem volume from the six year old trees at Woodhorn (Figure 2, Table 3) showed an unusual distribution of the data. These data were obtained from scans using a TLS and it is likely that the curvilinear distribution of the data reflects the functions used to convert the data from the points identified by the TLS to stem dimensions. Both the AFOCEL and Shell volume functions underestimate the volumes determined through use of the TLS. For the ten year old trees at Thoresby, the Shell function consistently underestimated stem volumes, while the AFOCEL function provided a more balanced estimate (Figure 3, Table 3). The AFOCEL function estimated the volumes of larger trees more precisely than for smaller trees (Figure 3). The residuals for estimates of stem volumes for the combined Chiddingfold and Glenbranter trees, of 28 years and 43 years of age respectively is shown in Figure 4. The Shell function again underestimated the volume of all trees, while the AFOCEL function provided a better and more balanced estimate (Table 3).

Study 2: Growth functions from stem analysis on trees from Chiddingfold and Glenbranter

A Richards function was selected as best fit for height growth at Chiddingfold (Table 5, Figure 5) and Glenbranter (Table 6). Polynomial functions provided a good characterisation of the relationship between height and DBH at Chiddingfold (Table 5) and at Glenbranter (Table 6).

Characterising growth proved more difficult, although good fit functions were developed for cumulative volume and for mean annual increment (Table 5 and Table 6). For these variables the best-fit functions gave negative values in the early years of growth and so they are only applicable to trees above six years old. A wide range of functions were applied to CAI data and also log transformed CAI data, including equations recommended in FAO [15]. However it was not possible to obtain a function that adequately represented growth due to

the rapid decline in CAI in the trees' later years, demonstrated by very narrow ring widths on the stem discs. This is likely to have been because the stands have not been thinned and so would be atypical of trees in managed stands.

The trees at Chiddingfold exhibited a considerable variation in growth rate, reflecting the high levels of competition in the unthinned stand. The dominant tree, tree1 had achieved an overbark stem volume of over 1 m^3 in 28 years, whereas the overbark volume of the smallest tree was only 0.047 m^3 (Table 4). The stem volume and increment data was not normally distributed and so the median rather than means of these variables was used to develop growth curves. For each tree from stem volume was converted to a volume per unit area using crown projection.

Trees at Chiddingfold have grown relatively slowly, with 200 m^3 ha^{-1} being achieved at 28 years old (Figure 8), giving an MAI of 7 m^3 ha^{-1} y^{-1}. EMIS was used to predict growth of alder (*Alnus glutinosa*), the most productive broadleaf at the site, which was estimated at a MMAI of 10 m^3 ha^{-1} y^{-1} and also the most productive conifer, western red cedar (*Thuja plicata*) which was predicted to achieve a MAI of 16 m^3 ha^{-1} y^{-1}. At 30 years old, the MAI of alder was estimated to be 9.3 m^3 ha^{-1} y^{-1}, while for western red cedar at 31 years old it was 10.9 m^3 ha^{-1} y^{-1} ([16]. There would therefore appear to be more productive trees than *E. gunnii* that can be grown at Chiddingfold. Only two trees were felled at Glenbranter for seed collection and were then available for stem analysis. A sample from seven 0.01 ha plots and 47 live trees gave a quadratic mean DBH of 30.8 cm and a mean height of 29.7 m. The two trees used for stem analysis had a quadratic mean DBH of 27.2 and a mean height of 26.6 m, so may underestimate growth of the stand as a whole. The trees at Glenbranter had reached an MAI of 4.5 m^3 ha^{-1} y^{-1} at age 30 years and 11.4 m^3 ha^{-1} y^{-1}at age 43 years.

The data reinforces the importance of good silviculture and maintenance. The stands at Chiddingfold and Glenbranter were unthinned. The stem analysis data showed that growth had slowed to almost zero in later years due to intense intra-stand competition. Furthermore, the initial growth of many of the older stands is likely to be slower that its potential due to lack of maintenance. The cumulative volume growth started to decline at Glenbranter later than at Chiddingfold possibly due to a lesser degree of competition, a result of lower stocking of the stand at Glenbranter. The patterns of CAI and MAI suggest that longer rotations than those suggested under short rotation forestry will maximise volume as MAI was still increasing in the final year before the trees were felled; 28 years at

Chiddingfold and and 43 years at Glenbranter. The MAI and CAI for the median tree at Chiddingfold is shown in Figure 9. For all but one of the nine trees MAI was still increasing at 28 years, the age at which they were felled. For the remaining tree, MAI peaked at 27 years. For the four largest trees CAI peaked at between 19 and 25 years of age, whereas for the two smallest trees it peaked between 14 and 20 years of age. In all trees CAI dropped considerably in the latter years, probably due to high competition in the unthinned stand. For the two trees felled at Glenbranter and MAI was still increasing at age 43 years.

4.3 Critique of the methods

Stem analysis is a common approach to obtaining growth data from forest trees and stands and was the only method to obtain annual growth data across a time period of a rotation. There were some considerable constraints to the application of this method. A major shortcoming is the small number of trees used in the study, especially from the site at Glenbranter. Furthermore, the lack of thinning meant that there was much more variation in the growth of the trees than there would have been in a managed stand.

The stem analysis method itself was hampered by the difficulty in discerning annual growth rings in some cases. This was due to three factors:

1. The lack of dormancy over warm periods in winter means annual growth is less defined than in most temperate trees.

2. The diffuse porous wood structure exhibited by *E. gunnii* made definition of rings less clear than in ring porous hardwood species.

3. The narrow ring widths or missing rings in later years of growth, due to high competition between trees in the unthinned stands at Chiddingfold and at Glenbranter.

Many temperate eucalypts display more or less annual rings, although a study of ageing trees of *Eucalyptus diversicolor* showed that this pattern was most reliable in dominant trees [Rayner 1992 in 17]. The lack of thinning and rapid growth meant that, to a degree most of the trees sampled were under considerable competition in their later years. Trees that are suppressed are known not to produce annual rings in lower portions of the stem, resources

being concentrated on height growth, rather than diameter [18]. In suppressed trees it is likely that the determination of annual rings was most reliable for the earlier years of growth, when the trees were under less competition. One suppressed tree from Chiddingfold was omitted from this study as the ring count at the base of the tree did not correspond to the known age of the tree. Ring counts from the discs cut up the tree stem were used to identify height attained as the tree developed. Comparison of the height curves based on historic mined data and on stem analysis (Figure 5) showed them to be similar, suggesting that the data from the stem analysis was reliable.

Conclusion

The precision of two volume equations were compared, one devised by AFOCEL [3] from plantations of *E. gunnii* and *Eucalyptus* X *gundal* in France and another developed by Shell [4] for cold-tolerant eucalypts in Chile. The AFOCEL equation gave a better fit for all but the smallest of trees, as the Shell function consistently underestimated stem volume.

While this investigation focused on the use of *E. gunnii* for short rotation forestry, the stem analysis indicated that MAI was still increasing at 28 years of age at Chiddingfold and 43 years old at Glenbranter. As such, volume production over time is likely to be maximised at longer rotations than the 15 years proposed by Hardcastle [19]. The results showed lower growth rates than had been obtained than yielded on other sites, however the stands have not been thinned and growth had slowed significantly indicated by narrow or missing annual rings in the trees' later years.

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