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Research paper

# Preliminary growth functions for *Eucalyptus gunnii* in the UK

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**Abstract**

This study represents the first attempt to develop growth functions for *Eucalyptus gunnii* grown in the UK. Functions relating height and age, height and DBH, cumulative volume and age and mean annual increment and age were developed using historic data. These indicated that stands in the UK achieved an average growth rate of 16 $m^3$ $ha^{-1}$ $y^{-1}$ or approximately 8 Mg $ha^{-1}$ $y^{-1}$ of dry stem biomass at an age of twenty years. There is evidence that yields can be considerably higher where intensive silviculture, such as use of plastic mulches and nutrient inputs has been practised, such as at Daneshill in Nottinghamshire, where trees attained a height of 10.6 m in five and a half years. However, potential yields are often compromised by high mortality and a priority should be to identify areas in the UK where *E. gunnii* can be grown with low risk and also to choose well adapted genetic material.

**Keywords:** *Eucalyptus*; United Kingdom; Short rotation forestry; Biomass; Volume; Growth; Yield

# 1 Introduction

Of the eucalypts, cider gum (*Eucalyptus gunnii*), a high altitude species, endemic to Tasmania is one of the hardiest species [1,2]. It has a long history in the United Kingdom, was the first Australian tree to be successfully grown outdoors and is now relatively common in gardens and parks [3]. There are specimens of individuals planted almost 100 years ago, a testament to the good adaptation of the species to parts of the UK where cold is not a limitation [3]. Results from provenance trials in the UK have indicated the superiority in growth and survival of the Lake McKenzie provenances [4,5] and there is potential for enhancing cold hardiness in *E. gunnii* through selection; Evans [4] described some individuals that had survived minimum temperatures of -18 °C.

The potential for improving yields of *E. gunnii* through tree improvement and rigorous silviculture can be observed in trials in France, where a long term pulp plantation programme has developed clones of *E. gunnii*, selected for productivity and cold tolerance. Furthermore, *E.* x *gundal*, a hybrid between *E. gunnii* and *E. dalrympleana* has been created, which combines the better growth rates and form of *Eucalyptus dalrympleana* with the greater cold tolerance of *E. gunnii*. Establishment and tending practices are intensive and growth from these plantations has been impressive; standing volumes of between 160 and 215 $m^3$ $ha^{-1}$ or mean annual increments of between 13 and 18 $m^3$ $ha^{-1}$ $year^{-1}$ of stem volume have been achieved over a 12 year rotation [6].

Growth of *E. gunnii* in the UK has been estimated in a small number of studies [5,7], but there are no continuous measurements of volume growth. Table 1 describes some of the published estimates of growth reported in the literature and from personal communications. All the estimates of volume were based on measurements of DBH and height, from which stem volume is estimated making certain assumptions on stem form. The annual increments in weight for the New Forest study were calculated from volumes and an assumed wood density, but for Daneshill the values were based on the actual weight harvested and chipped and includes branches. Table 2 presents results of growth from trials growing *E. gunnii* as short rotation coppice.

**Table 1** Published and other information on growth rates of non-coppiced *E. gunnii* in the UK.

alt-text: Table 1

| Location | Age (years) | Standing volume or biomass | Mean annual increment | Notes |
|---|---|---|---|---|
| Daneshill[1] | 5 | 85 ~~t~~ Mg ha$^{-1}$ | 17 Mg ha$^{-1}$ y$^{-1}$ | From a mix of stands of *E. gunnii* and the more productive *E. nitens*. Dead stems were standing for six months so wood was relatively dry. Stocking approximately 2940 ha$^{-1}$ |
| New Forest[2] | 7 | 97 m$^3$ ha$^{-1}$ | 13.9 m$^3$ ha$^{-1}$ y$^{-1}$/6.2 Mg ha$^{-1}$ y$^{-1}$ | From a spacing experiment, planted at 5102 ha$^{-1}$. Biomass production is on a dry weight basis. |
| New Forest[2] | 7 | 19 m$^3$ ha$^{-1}$ | 2.7 m$^3$ ha$^{-1}$ y$^{-1}$ | From a spacing experiment, planted at 1276 ha$^{-1}$ |
| Thetford[3a] | 21 | 261 m$^3$ ha$^{-1}$ | 12.4 m$^3$ ha$^{-1}$ y$^{-1}$ | From small, line plots in a provenance trial, planted at 1850 ha$^{-1}$ with 48% survival giving 888 ha$^{-1}$. |
| Glenbranter[4b] | 25 | 452 m$^3$ ha$^{-1}$ | 18.1 m$^3$ ha$^{-1}$ y$^{-1}$ | From small, line plots in a provenance trial, planted at 1842 ha$^{-1}$ with 96% survival giving 1768 ha$^{-1}$ |
| Chiddingfold[5c] | 25 | 435 m$^3$ ha$^{-1}$ | 17.4 m$^3$ ha$^{-1}$ y$^{-1}$ | From two 0.01 ha plots measured in a small block planting, mean stocking of 1150 ha$^{-1}$. |

[1] [8],[2] [7],[3] [9],[4] [5],[5] [10]. [a] Mean of three provenances,[b] Mean of five Lake McKenzie seed lots. [c] Mean of two provenances.

**Table 2** Published and other information on growth rates in Mg dry matter per hectare per year of short rotation coppice *E. gunnii* in the UK and Ireland.

alt-text: Table 2

| Location | Age (years) | Mean annual increment (Mg ha$^{-1}$ year$^{-1}$) | Notes |
|---|---|---|---|
| University College Dublin[1] | 1[a] | 12.6 | Planted at 2657 ha$^{-1}$ |
| University College Dublin[1] | 1[a] | 15.4 | Planted at 3267 ha$^{-1}$ |
| Long Ashton[3] | 2[b] | 13.0 | Planted at 10 000 ha$^{-1}$ |
| Long Ashton[3] | 2[b] | 9.9 | Planted at 2500 ha$^{-1}$ |
| Mepal[3] | 2[b] | 12.7 | Planted at 10 000 ha$^{-1}$ |
| Mepal[3] | 2[b] | 4.2 | Planted at 2500 ha$^{-1}$ |
| Whitney[3] | 2[b] | 4.7 | Planted at 10 000 ha$^{-1}$ |
| Whitney[3] | 2[b] | 2.5 | Planted at 2500 ha$^{-1}$ |
| Long Ashton[2] | 4[b] | 18.4[b] | Planted at 10 000 ha$^{-1}$ but 60% survival, so 6000 ha$^{-1}$ |
| Long Ashton[3] | 4[b] | 13.5 | Planted at 10 000 ha$^{-1}$ |
| Long Ashton[3] | 4[b] | 8.3 | Planted at 2500 ha$^{-1}$ |

[1] [11],[2] [12],[3] [13]. [a] But stools are 13 years old and been successively harvested every year. [b] Age of shoots after being cut back to initiate coppice at one year old.[c] mean of yields in 1985/86 and 1986/87.

To understand the pattern of growth over time and conduct economic analyses, growth curves are required. For *E. gunnii,* the only growth curves published are from plantations in France [14,15]. There are no growth curves for trees grown in the UK and no continuous time series data sets in the UK covering the predicted rotation lengths for short rotation plantations of *E. gunnii*. There are however data from measurements of height and diameter or height alone at a point in time or sometimes several measurements over a restricted period of time from trials established by Forest Research from the 1980s and a few other trials. Most of these provide data on growth in the first five years but there are a few measurements of older trees.

This study was devised to provide preliminary estimates of stem growth of *E. gunnii* in the UK and the aim was to develop a generalised growth curve relating volume per unit area to stand age.

# 2 Methods and analysis

The lack of continuous growth data and limited geographical spread of plantings of *E. gunnii* in Britain present a considerable problem when developing a generalised growth curve. Data on growth were extracted from files of trials established by Forest Research, Nottinghamshire County Council and Thoresby Hall Estate and means for stands at the sites calculated for height and, where available, for DBH. These data are summarised in Table 3 and the locations in Fig. 1. Age in years is presented to two decimal places (one decimal place is not sufficiently precise to differentiate between months; for example both 3 months and 4 months rounded would be 0.3 years).

**Table 3** Tree size data: location, height, DBH, sample size and stocking.

alt-text: Table 3

| | Age (months) | Age (yrs) | Height (m) | N | DBH (cm) | Stocking (number $ha^{-1}$) |
|---|---|---|---|---|---|---|
| Chiddingfold | 5 | 0.42 | 0.5 | 59 | | 1313 |
| Chiddingfold | 14 | 1.17 | 1.4 | 58 | | 1291 |
| Chiddingfold | 26 | 2.17 | 1.2 | 50 | | 1113 |
| Chiddingfold | 29 | 2.42 | 1.5 | 975 | | 1716 |
| Chiddingfold | 38 | 3.17 | 2.3 | 49 | | 1091 |
| Chiddingfold | 85 | 7.08 | 5.4 | 975 | | 1202 |
| Chiddingfold | 311 | 25.92 | 22.8 | 23 | 19.1 | 1150 |
| Chiddingfold | 336 | 28.00 | 19.4 | 10 | 19.2 | N/A |
| Dalton | 5 | 0.42 | 0.7 | N/A | | 2500 |
| Dalton | 16 | 1.33 | 1.3 | N/A | | 2317 |
| Dalton | 35 | 2.92 | 2.0 | N/A | | 2317 |
| Dalton | 282 | 23.50 | 17.8 | N/A | 23.3 | 2584 |
| Daneshill | 28 | 2.33 | 5.4 | 14 | 8.3 | 2940 |
| Daneshill | 41 | 3.42 | 7.6 | 14 | 12.3 | 2940 |
| Daneshill | 53 | 4.42 | 8.1 | 14 | 11.4 | 2940 |
| Daneshill | 65 | 5.42 | 10.6 | 13 | 12.4 | 2940 |
| Glenbranter | 29 | 2.42 | 1.2 | 78 | | 1330 |
| Glenbranter | 34 | 2.83 | 1.2 | 78 | | 1330 |
| Glenbranter | 54 | 4.50 | 2.5 | 79 | | 1347 |
| Glenbranter | 107 | 8.92 | 9.3 | N/A | 8.6 | N/A |
| Glenbranter | 120 | 10.00 | 9.7 | 79 | 9.8 | 1347 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Glenbranter | 178 | 14.83 | 15.8 | 5 | 13.7 | N/A |
| Glenbranter | 308 | 25.67 | 14.9 | 74 | 19.1 | 1262 |
| Glenbranter | 516 | 43.00 | 30.1 | 45 | 35.2 | N/A |
| New Forest | 5 | 0.42 | 0.1 | 130 | | 1275 |
| New Forest | 45 | 3.75 | 7.2 | 130 | | 1275 |
| New Forest | 53 | 4.42 | 7.3 | 130 | 5.8 | 1275 |
| New Forest | 75 | 6.25 | 10.5 | 130 | 8.0 | 1275 |
| Thoresby | 126 | 10.50 | 16.4 | 35 | 20.7 | 2500 |
| Tintern | 2 | 0.17 | 0.4 | 60 | | 3265 |
| Tintern | 16 | 1.33 | 1.2 | 28 | | 3265 |
| Tintern | 28 | 2.33 | 1.4 | 63 | | 3265 |
| Tintern | 29 | 2.42 | 2.0 | 59 | | 3265 |
| Tintern | 43 | 3.58 | 3.5 | 28 | | 3265 |
| Tintern | 55 | 4.58 | 3.5 | 63 | | 3265 |
| Wykeham | 18 | 1.50 | 1.5 | N/A | | N/A |

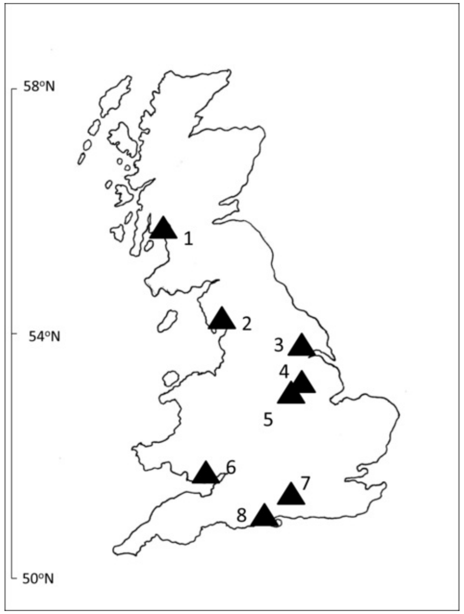


**Fig. 1** Locations of stands contributing growth data: 1 = Glenbranter (56°06′54N, 005°04′02W) 2 = Dalton (54°17′05N, 002°50′30W), 3 = Wykeham (N/A), 4 = Daneshill (53°21′50N, 000°58′57W), 5 = Thoresby (53°26′32N, 000°59′39W), 6 = Tintern (51°44′37N, 002°41′01W), 7 = Chiddingfold (51°03′49N, 00°035′29W) and 8 = New Forest (50°23′38N, 001°38′35E).

alt-text: Fig. 1

These data were used to develop a height by age curve, a DBH by height curve and through applying the AFOCEL volume function a stem volume by age curve. Due to the small amount of data available in general and of time-series data in particular, equations proven to accurately model height by age were applied to the historic UK data. The equations used [16,17] are shown below:

**1** Gompertz model: $y = a \cdot \exp(-\exp(b^{-cx}))$

**2** Exponential model: $y = a \cdot \exp(b(x + c))$

**3** Richard's model: $y = a \cdot (1-\exp(b \cdot x)^{c})$

**4** Korf model: $Y = a \cdot (\exp(b \cdot x^{-c})$

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

To enable volume growth to be estimated, a function relating diameter to height was also required. As diameter is strongly influenced by stocking, only data on diameter from trees planted at stockings of between 1200 and 2500 ~~trees~~ $ha^{-1}$ were used to derive a relationship between height and DBH using regression. To derive this relationship, the curve fitting tool in SPSS v19 was used which enables eleven different types of function to be fitted.

All height data across the range of stockings was used to fit a height: age curve, as height is relatively independent of stocking. This was undertaken using the nonlinear regression tools in SPSS v19.

To obtain a preliminary estimate of volume growth across Britain, the predicted height and predicted DBH at those heights up to an age of twenty years were converted to volumes using the AFOCEL volume function (see additional web material) to obtain a stem volume for trees up to twenty years. The AFOCEL equation incorporated height and diameter at breast height, where V = overbark volume ($m^3$), DBH = diameter at breast height (cm) and h = height (m).

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

The analysis was restricted to the first twenty years as self thinning and other mortality is likely to have had an impact on stocking in later years. Also, growth after 20 years is likely to have been less than that of well managed stands due to the onset of inter-tree competition, with all but the dominant trees in the stands being affected. A median initial stocking of 1350 ~~trees~~ $hectare^{-1}$, based on the stands sampled was used to convert stem volume to volume per hectare and it was assumed there was no mortality.

# 3 Results

Nonlinear regression of height against age was undertaken using four commonly used functions and the Richard's function was found to give the best fit in terms of high $R^2$ and low standard error (Table 4). The curve derived from the Richard's equation is shown graphically in Fig. 2, with the height curve from French plantations [15] superimposed.

**Table 4** Description of the best fit models for age and height and height and DBH.

alt-text: Table 4

| X | y | Model | N | $r^2$ | SEE | A | B | c |
|---|---|---|---|---|---|---|---|---|
| Age (years) | Height (m) | Richards | 34 | 0.911 | 2.370 | 43.16 | −0.022 | 0.851 |
| Height (m) | DBH (cm) | Linear[a] ($y = a+b \cdot x$) | 15 | 0.843 | 3.181 | 0.797 | 1.044 | – |

[a] Where Y is DBH and X is height and a and b are parameters for the model.

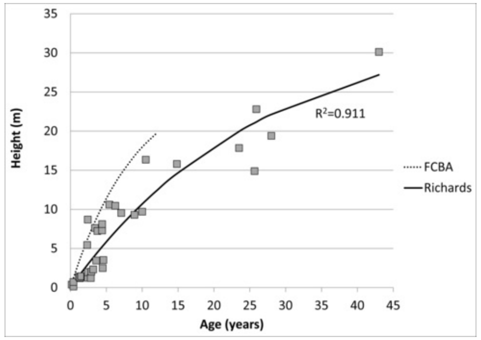


**Fig. 2** Mean plot heights by age with fitted Richards' function and in comparison the FCBA height curve [15]. FCBA height function is based on trees up to 12 years old and so has not been applied to older trees.

alt-text: Fig. 2

Eleven types of function were used in regression of DBH against height and were compared through $R^2$ and standard error. Of these a linear relationship provided the best fit to the data, in terms of a high $R^2$ and lowest SEE (Table 4 and Fig. 3).

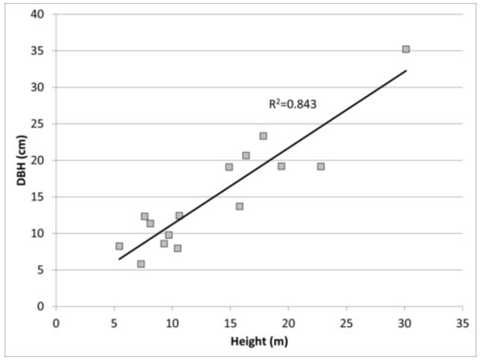


**Fig. 3** Relationship between dbh and height, with best fit line.

alt-text: Fig. 3

Using the two functions, height and DBH at ages up to 20 years were estimated and stem volumes for each age from five to twenty years was calculated using the AFOCEL function. The standing volume curve using this approach is shown in Fig. 4 and values for stem volume, stem biomass and mean annual increment are presented in Table 5. Mean annual stem volume increment over a twenty year rotation was 16 $m^3$ $ha^{-1}$ $year^{-1}$ and applying a basic density of 500 kg $m^{-3}$ [18], gives a mean annual dry weight increment of 8 Mg $ha^{-1}$ $year^{-1}$.

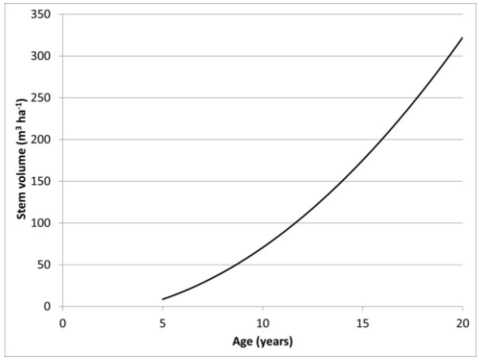


**Fig. 4** Predicted standing overbark stem volume by age, with tree volume calculated using dbh and height estimated from the age: height function and height:dbh function and volume from the AFOCEL function. Stocking was assumed to be a constant 1350 ~~trees~~ ha$^{-1}$.

alt-text: Fig. 4

**Table 5** Predicted DBH, height, stem volume and volume per hectare (assuming stocking density of 1350 ha$^{-1}$) by age using best fit functions for height and age, DBH and height and the AFOCEL volume function.

alt-text: Table 5

| Age (year) | Height (m) | DBH (cm) | tree volume ($m^3$) | Volume per unit area ($m^3$ $ha^{-1}$) | dry weight per unit area (Mg $ha^{-1}$) | MAI ($m^3$ $ha^{-1}$ $y^{-1}$) |
|---|---|---|---|---|---|---|
| 5 | 6.3 | 7.4 | 0.007 | 9.6 | 4.8 | 1.9 |
| 6 | 7.3 | 8.4 | 0.013 | 17.9 | 9.0 | 3.0 |
| 7 | 8.2 | 9.4 | 0.021 | 28.1 | 14.0 | 4.0 |
| 8 | 9.1 | 10.3 | 0.030 | 40.1 | 20.1 | 5.0 |
| 9 | 10.0 | 11.3 | 0.040 | 54.0 | 27.0 | 6.0 |
| 10 | 10.9 | 12.1 | 0.052 | 69.8 | 34.9 | 7.0 |
| 11 | 11.7 | 13.0 | 0.065 | 87.5 | 43.7 | 8.0 |
| 12 | 12.4 | 13.8 | 0.079 | 106.9 | 53.5 | 8.9 |
| 13 | 13.2 | 14.6 | 0.095 | 128.1 | 64.1 | 9.9 |
| 14 | 13.9 | 15.4 | 0.112 | 151.0 | 75.5 | 10.8 |
| 15 | 14.7 | 16.1 | 0.130 | 175.5 | 87.8 | 11.7 |
| 16 | 15.3 | 16.8 | 0.149 | 201.6 | 100.8 | 12.6 |
| 17 | 16.0 | 17.5 | 0.170 | 229.3 | 114.6 | 13.5 |
| 18 | 16.7 | 18.2 | 0.191 | 258.3 | 129.2 | 14.4 |
| 19 | 17.3 | 18.9 | 0.214 | 288.7 | 144.4 | 15.2 |
| 20 | 17.9 | 19.5 | 0.237 | 320.5 | 160.2 | 16.0 |

# 4 Discussion

This study represents the first work to characterise growth curves of *E. gunnii* in the UK and the results are discussed below. The wide spread in the data (Fig. 2) for height by age reflects genetic differences between the trees, variations in the quality of silviculture and the range of site conditions at which these data were collected. A Richards' function described over 90% of the variation in the relationship between age and height (Table 4). Diameter is more strongly influenced by growing space than height and across the stands that provided the historic data, differences in initial spacing and subsequent mortality had resulted in a wide range of growing space. This variation and the small number of records of DBH made modelling the relationship between height and diameter imprecise. To narrow the range of growing space, only data from stands with initial stocking of between 1200 and 2500 ~~trees~~ ha$^{-1}$ were used. Fig. 3 shows the results based on mean data from 15 different measurements and a linear function explained 84% of the variation (Table 4).

Combining the age:height curve, the DBH:height curve and the AFOCEL volume function, stem volume growth was predicted (Fig. 4) over twenty years. This period was used for two reasons: it is close to the predicted 15 year rotation for *E. gunnii* grown for biomass [19] and for these unthinned stands that provided the data, competition was probably not overly intense, providing some indication of potential yield of managed stands. The volume growth curve gave a standing stem volume of 320 m$^3$ ha$^{-1}$ at 20 years of age, giving a mean annual increment of 16 m$^3$ ha$^{-1}$ y$^{-1}$ or an estimated dry mass increment of 8 Mg ha$^{-1}$ y$^{-1}$. Growth of these trees was considerably slower than the intensively managed stands in France, where volumes of 200 m$^3$ ha$^{-1}$ are achieved in 12 years [14], compared with around 16 years from the British stands (Table 5 and Fig. 4).

It is clear from the data mining exercise that there is considerable variation in growth between trees within stands and also between stands at different locations and grown under different intensities of silviculture. As such, the results from this study represent a first and highly generalised attempt at characterising *E. gunnii* growth under British conditions, based on a limited amount of data. At sites, such as Daneshill (Nottinghamshire) and the New Forest (Hampshire) a height of 10 m has been achieved at 5 or 6 years of age. Daneshill was the only site where intensive silviculture was practiced, and the intensive establishment methods used, such as planting the trees through biodegradable plastic sheeting, a technique to inhibit weed competition and the use of high nitrogen sewage sludge as a biofertiliser are likely to explain the rapid growth. At other sites, where more conventional establishment was practiced, such as at the more northerly one at Glenbranter the same height was only reached in ten years.

## 4.1 Critique of the methods

This study represents the first characterisation of growth of *E. gunnii* in the UK and enables a broad comparison with other tree species suited to biomass production. The study has collated all historic data that was available, from a number of sources and so represents the best information currently available. It is acknowledged that these data represented relatively few sites, but that they showed a reasonable distribution across the UK (Fig. 1). Each site also provided only a limited amount of chronological data and that there were more data for tree height and furthermore the analysis of DBH data was complicated by the range of spacing employed across the plantings. To reduce this variation, data from a restricted range of spacing was used to determine the relationship between DBH and height. Should *E. gunnii* be more extensively planted in the UK it is recommended that permanent growth plots be established across the range of sites where it is established to obtain a chronological series of data and to determine differences in growth due to climate, soils and other factors.

## 4.2 Wider implications of the findings

On warmer sites, eucalypts in general and *E. gunnii* specifically offer the opportunity to rapidly grow woody biomass over short rotations. Kerr [20] recognised the potential and described eucalypts and *Nothofagus* spp. as the fastest growing groups of trees in the UK. This study supports his observations; at Daneshill in Nottinghamshire, stands of *E. gunnii* achieved a height of over 10 m at five and a half years of age, a result of intensive establishment using complete cultivation and the use of a plastic mulch to control weed competition and sewage sludge as a nitrogen rich fertiliser. However, it took more than ten years for trees to reach the same height at Glenbranter, a colder site in south west Scotland and where establishment techniques were less intensive (Table 3). Currently, predicting the influence of factors such as site and establishment techniques on growth is imprecise, for example trees at Thoresby Estate in Nottinghamshire were relatively neglected, yet grew rapidly attaining a height of over 16 m in 10 years. However, normally high rates of growth are obtained when *E. gunnii* is planted on appropriate sites in conjunction with intensive silviculture.

High mortality of *E. gunnii* in many plantings has had a major impact on potential productivity and if planted on a greater scale then sites unsuitable for *E. gunnii* need to be identified. In the mid Pyrennes in France a zonation of sites by climate and soils was developed to predict the risk of cold damage to *E. gunnii* and *E. gundal* [21]. Across France, four zones were defined in terms of the suitability of climate and soils, based on tolerable minimum thresholds of mid-winter temperatures and the risk of lime induced chlorosis. Zonation was based on the average number of days when minimum mid-winter temperatures of -12 °C for *E. gundal* and -18 °C for *E. gunnii* were exceeded. A similar approach could be adopted to identify sites appropriate for planting *E. gunnii* in the UK, which could follow that of the maps produced for *Nothofagus nervosa* in Hardcastle [19]. The risk of high mortality of eucalypts would be further reduced by the use of genetic material that was well adapted to UK conditions.

*E. gunnii* is known as being particularly cold hardy but is not the most productive eucalypt species grown in the UK. It also has poor stem form and its foliage is palatable, increasing the potential of damage from browsing. However on suitable sites productivity will be higher than most native or naturalised trees and a further justification for planting *E. gunnii* is the drive to broaden the range of trees species planted in production forestry in the UK [22].

Results from historic and recent trial plantings and indicate that other species of eucalypts can be successfully grown in warmer parts of the UK. For example *Eucalyptus glaucescens*, that offers lower cold tolerance but greater productivity, better stem form and is less prone to damage by browsing mammals [23].

# 5 Conclusion

The relative cold hardiness of *E. gunnii* offers an opportunity to grow *Eucalyptus* across a wider range of sites than is possible with other *Eucalyptus* species. The small area of planting of *E. gunnii* in the UK and a lack of time series data makes predicting growth rates difficult for specific sites. It is clear however that on certain sites high yields of woody stem biomass of 8 Mg ha$^{-1}$ y$^{-1}$ or more are possible from *E. gunnii* in the UK, but that it has been inconsistently achieved in practice. The growth at Daneshill provides evidence of the benefits of intensive silviculture and it recommended that similar establishment practices be adopted if productivity is to be maximised. To ensure good survival and effective site capture it is also recommended that planting be confined to warmer areas in the UK until a better understanding of site suitability is achieved. While *E. gunnii* is not a species that will be widely planted due to the cold, it can extend the range of tree species available for planting for biomass.

# Acknowledgements

This study could not have been completed without the help of many people. Dr Richard Jinks kindly provided all files of experiments using *E. gunnii* at Forest Research, while Ted ~~Woodisse~~Wooddisse provided data from the trials established at Daneshill by Nottinghamshire County Council. Site information on Glanbranter was kindly supplied by Fraser MacDonald of Forestry Commission Scotland. We would also like to thank the two anonymous reviewers for their constructive comments and Dr James Morison of Forest Research for comments on an earlier draft of the paper. Finally the authors would like to acknowledge funding for some of the work from the University of Cumbria's Research, Scholarship and Development Fund.

# Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.biombioe.2017.10.037.

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# Appendix A. Supplementary data

The following is the supplementary data related to this article:

Multimedia Component 1

**Supplementary material** **(Please substitute the original supplementary materials file with the one attached.)**

alt-text: Supplementary material

**Highlights**

- Historic growth of *E. gunnii* indicated yields of 16 $m^3$ $ha^{-1}$ $y^{-1}$ or 8 Mg $ha^{-1}$ $y^{-1}$ over 20 year rotations.
- Yield was highly variable across sites but it is likely that intensive silviculture increases yields.
- ~~Until there is a better understanding of the climatic limits to survival and growth planting should focus on sites with low risk of frost~~. Until climatic limits to survival and growth are better understood, planting should be on sites with low risk of frost. .

## Queries and Answers

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