Biomass and Bioenergy 108 (2018) 464–469

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Preliminary growth functions for *Eucalyptus gunnii* in the UK

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ARTICLE INFO

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

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.

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.

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.

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http://dx.doi.org/10.1016/j.biombioe.2017.10.037
Received 28 June 2017; Received in revised form 24 October 2017; Accepted 25 October 2017
Available online 02 November 2017

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

Location	Age (years)	Standing volume or biomass	Mean annual increment	Notes
Daneshill[1]	5	85 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.

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).

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 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 $hectare^{-1}$, 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.

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