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## Modelling growth of volume sample and stem analysis trees with reference to site conditions in Wales

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## Modelling Growth

OF

# Volume Sample and Stem Analysis Trees with Reference to Site Conditions in Wales 

Being a thesis submitted in candidature for the degree of Doctor of Philosophy
by

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#### Abstract

Concerns over sustainability and a move towards systems of forest management other than clearfelling have fuelled the search for flexible growth models that can be used in a wide variety of situations with wide generalisation. The Tyfiant Coed project was established to develop a distance dependent individual tree model based on earlier stand level approaches. The model is parameter parsimonious and the parameters are interpretable. In particular the primary growth parameter, $c_{1}$, is considered to reflect the vitality of a tree and is itself influenced by competition factors and environmental conditions. After preliminary parameterisation work using German data, Tyfiant Coed has attempted to establish suitable parameters for a flexible growth and yield model for Sitka spruce (Picea sitchensis (Bong.) Carr.). This study describes methods of collecting data suitable for the establishment of model parameters and initial investigations into the relationship of the parameters with broad environmental variables. A rapid method was used to gather data from a wide variety of site types in north and mid Wales. Using these data alternative parameter values for individual trees and stands were estimated. These parameters were compared to values derived from stem analysis. The ability of the model to reproduce the pattern of individual tree growth was also examined. Using linear regression techniques parameter values were compared with environmental factors to determine whether any relationships existed. The suitability of the methodology and its potential for use in modelling in Britain are discussed. Suggestions for further work are made.


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Sadly, Professor Wenk passed away just a few days before the submission of this thesis.

## 1 INTRODUCTION

### 1.1 Background and context

Concern for the environment, sustainability of production and the concept of multi-use forestry have led to an increasing interest in silvicultural systems that fall under the general heading of continuous cover forestry (Forestry Commission, 2004). In Great Britain, following devolution and the establishment of National Parliaments, this was reflected in forest strategies for England, Scotland and Wales (Forestry Commission, $1999,2000,2001$ ) which contained commitments to expand the use of continuous cover forestry (CCF) in both state and private woodlands. This commitment has been particularly strong in Wales, where the aim has been to:
> convert at least half of the National Assembly woodlands to continuous cover over the next 20 years, where practical, and encourage conversion in similar private sector woodlands (Forestry Commission, 2001).

The term CCF encompasses many different concepts and silvicultural systems and CCF principles can be used to achieve a wide range of management objectives. The underlying principle is that tree cover should be maintained and large scale clearfelling avoided and CCF may include, for example, greater emphasis on mixed stands, with no fixed rotation period, and the promotion of native species (Mason et al., 1999; Pommerening and Murphy, 2004). In Britain the forest industry has been geared towards maximum volume production (Forestry Commission, 2002) and existing forest management generally favours monospecific stands grown over relatively short rotations culminating in clearfelling. The main commercial tree species are conifers, in particular Sitka spruce (Picea sitchensis (Bong.) Carr.). CCF is not widely practiced, only a small proportion of the public and private forest estate being managed in this way, and there is a deficiency in experience and knowledge amongst practitioners (Hart, 1995; Mason, 2002).

As well as silvicultural and management issues there are social and economic questions to be addressed as well as broader environmental issues, such as the impact of predicted climate change (Pretzsch, 1996; Broadmeadow, 2002; Broadmeadow and Ray, 2005). None can be taken in isolation and to address these issues foresters need to take account
of new ideas and working practices, there being an urgent need for decision support systems that will enable foresters to make reasonable and informed judgements (Mason and Kerr, 2001; Pommerening and Wenk, 2002). One of the requirements is for updated yield forecasting that is flexible enough to encompass both existing management systems and mixed age, mixed species silviculture (Pretzsch, 2002) and the lack of a suitable management level growth and yield model in Britain has been recognised (Mason, 1999).

Therefore the commitment to CCF represents a major challenge for British foresters. Woodlands for Wales recognises this and there is a commitment to develop education and training and to promote best practice in woodland management with a clear aim:
to gather information about continuous cover systems and how best to manage these systems for the range of benefits that society demands. (Forestry Commission, 2001).

This investigation was part of the Tyfiant Coed Project which was established to gather information on CCF systems and practice, and to begin development of a growth model which would have the flexibility to be applied to a wide range of silvicultural scenarios (Pommerening, 2002, 2005). Tyfiant Coed was, therefore, an important part of the National Assembly's commitment to changing the fundamental character of the forest industry in Wales.

### 1.2 Tyfiant Coed

Tyfiant Coed, a Welsh term meaning "tree growth", is a single tree, distance dependent model (von Gadow and Hui, 1999) established to predict the growth and development of Sitka spruce and birch (Betula spp.) in Welsh forests (Pommerening and Wenk, 2002). The model is based on earlier approaches for stand level predictions by Wenk (1994) and uses growth multipliers and generalised allometric relationships to predict tree growth. The multipliers are derived from relative increment which itself is estimated from a growth function. The Tyfiant Coed model uses a modified Gompertz function which has parameters designated $c_{1}$ to $c_{4}$ (equation 1.1).

where:

```
p
c},\mp@subsup{c}{2}{},\mp@subsup{c}{3}{},\mp@subsup{c}{4}{
t
parameters
transformed age (section 2.4.5)
```

The parameters, in particular $c_{1}$, are interpretable and are indicative of the vitality of the tree or productivity of the stand. At any given age, the greater the value of $c_{1}$, the lower the value of relative increment (see Fig. 2.2). Parameters $c_{2}$ and $c_{3}$ account for variations in the early growth stages of the tree or stand and lose their influence beyond 60 years of age. Parameter $c_{4}$, if used, modifies growth at ages beyond about 100 years. The primary focus of the model is on volume prediction in order to minimise error propagation when estimating other tree characteristics such as diameter and height. The mechanistic nature of the basic growth function has an empirical foundation, though there is a relatively small data demand and a high degree of generalisation The model properties allow forecasting with a high degree of flexibility. Pommerening and Wenk (2002) developed a preliminary model using data from long term experimental plots of Norway spruce (Picea abies (L.) Karst.) in Germany.

### 1.3 Objectives

One of the priorities identified by Pommerening and Wenk (2002) was the necessity of linking the parameters of the Tyfiant Coed growth model to environmental conditions. This would give the model the required general applicability for use throughout Wales and flexibility in the event of climate change. When the project was first established little was known of the likely magnitude and range of values of the model parameters for Sitka spruce growing in Britain. Data provided by Forest Research, the research agency of the British state forestry service, covered only a narrow range of site types and also required detailed analysis in order to establish model parameters (Pommerening, 2002). It was, therefore, necessary to establish permanent research plots in order to collect more data. This entailed a delay of five years for a second enumeration before the first of these data became available. The aim of this project was
to provide values of the model parameters, in particular parameter $c_{1}$, from different site types and investigate the relationship between the parameters and environmental variables. An important aspect of this was that the data should be capable of being gathered relatively quickly from a greater number and wider range of sites types than would be provided by the network of permanent plots. The main objectives are summarised below.

1. Establish a number of temporary sample plots on as wide a range of site types as possible.
2. Gather data suitable for estimating model parameters.
3. Test techniques for gathering the data.
4. Compare methods of estimating parameters.
5. Investigate the variation in parameter values within and between different stands.
6. Examine the relationship between stand $c_{1}$ and individual tree $c_{1}$.
7. Investigate possible links between site factors and model parameters.

In this investigation parameters were estimated using modified versions of equation (1.1) and equation (2.9).

## 2 MODELLING

### 2.1 Model Types

A model is an abstract representation which assists our understanding, interpretation and utilization of the real world. They vary in kind and level of detail from, for example, simple written or spoken descriptions to complex mathematical functions requiring large amounts of computing capacity (Kimmins, 1996). Modern forest growth models generally fall into the latter category.

In the context of forestry a model can be used to represent individual trees or parts of trees, whole stands, or some part of them, and regions (von Gadow and Hui, 1999). Ideally models should be goal oriented, i.e. have a defined purpose (Vanclay, 1994). There are many possible reasons for which it might be desirable to construct a model and equally as many model types developed to meet the objective in mind. Peng (2000) lists over 40 growth and yield models, for uneven aged stands, that have been created over the past 100 years and, though yield tables have been in use since the late $18^{\text {th }}$ century (Porté and Bartelink, 2002), the majority of these have originated since 1980. Possible uses of models are for improving understanding of individual processes and key components in tree growth, to aid silvicultural decision making and for the assessment of growth under different environmental conditions.

Models can be classified in different ways, for example by the method of construction, by their purpose, or their resolution (Clutter et al., 1983; Vanclay, 1994; Peng, 2000). Fig. 2.1 provides a general classification of forest growth models though it must be emphasized that there is much overlap between model types. Von Gadow and Hui (1999) point to the desirability of being able to integrate models of different resolution which they liken to a telescope which, if extended, will show different levels of detail. As yet, however, no single universal model has been developed which suits all objectives and there has been and possibly remains an antagonism between empirical modelling for management purposes and process based modelling for understanding tree growth and projecting stand development under changing circumstances (Yaussy, 2000).


Figure 2.1 Classification of growth models
Model types increase in complexity from stand level to complex process models based on individual trees. Standard yield tables, such as those of the Forestry Commission (Edwards and Christie, 1981) are relatively easy to construct and have provided excellent tools for predicting yield in single species plantations. However they have limited application for mixed age, mixed species stands and, as they rely on historical data, lack the flexibility required to account for changing environmental conditions (Kimmins, 1996). At the opposite extreme process simulation models are complex and attempt to model the processes and interactions involved in tree growth (e.g. Botkin, 1993). Kimmins (1996) provides a summary of the various types. The data requirements and complexity of these models limits their usefulness as practical management aids although they are powerful research tools and may be better suited to investigating the impact of potential climate change than purely empirical models based on historical data (Waring, 2000). So called hybrid models attempt to bridge the divide between these two extremes and incorporate elements of both types (Kimmins, 1996). Hasenauer (2006) identifies a fundamental difference between stand level and individual tree models. The former are based on average values and are used to forecast mean stand development. Their conceptual basis is that of a reference stand for each species and site index. The conceptual basis of tree growth models is the individual tree and this offers the forest scientist, in theory at least, unlimited flexibility in developing models for different silvicultural scenarios.

### 2.2 Basic Functions and data sources

### 2.2.1 Functions

Fundamental to any model are the functions that describe the growth of the individual trees and stands or describe the relationships between individual components and many text books are available which discuss these (Bruce and Schumacher, 1950; Prodan, 1968; von Gadow and Hui, 1999). In forestry most of these functions have had a strictly empirical nature relying on observation of the geometric pattern in the data and fitting curves which have no theoretical or biologically plausible basis (Pienaar and Turnbull, 1973). Schumacher (1939) is credited with attempting to put a more theoretical basis to modeling stand development. He recognized that relative volume increment had an inverse relationship with age and developed functions that could relate volume development to age for a given site index (equation 2.1), the basic form of which is still widely used today (von Gadow and Hui, 1999):

$$
\begin{equation*}
\ln V=a_{0}+a_{1}\left(\frac{1}{A}\right)+a_{2} S I+a_{3}\left(\frac{S I}{A}\right) \tag{2.1}
\end{equation*}
$$

where

| $V$ | tree volume |
| :--- | :--- |
| A | tree age |
| SI | site index |
| $a_{0}, a_{1}, a_{2}, a_{3}$ | site specific parameters |

Pienaar and Turnbull (1973) also developed a more theoretical approach and investigated the possibility of using the Chapman-Richards generalization of von Bertalanffy's growth function (von Bertalanffy, 1949; Richards, 1959; Chapman, 1961). von Bertalanffy hypothesised that the rate of volume growth was determined by the interaction of the two competing components of metabolism (anabolism and catabolism) expressed mathematically as:

$$
\begin{equation*}
\frac{d V}{d t}=\eta V^{\frac{2}{3}}-\gamma V \tag{2.2}
\end{equation*}
$$

where

```
V tree volume
t time
\eta,\gamma coefficients of anabolism and catabolism
```

The exponent, $2 / 3$. is the result of an allometric (see section 2.4.8) relationship between surface area and volume growth of the organism and in the generalized form of the equation is replaced by the symbol, $m$. Integrating this equation eventually leads to the growth equation:

$$
\begin{equation*}
V_{1}=A\left[1-e^{-k\left(1-t_{0}\right)}\right]^{\frac{1}{1(-m)}} \tag{2.3}
\end{equation*}
$$

where
A asymptotic maximum volume
$t \quad$ time ( at $t=t_{0}, V_{t}=0$ )
$k$ constant
$m \quad$ allometric constant
Particular values of $m$ result in well known classic growth functions (Pienaar and Turnbull, 1973): mono-molecular growth $(m=0)$ and the logistic function $(\mathrm{m}=2)$. As $m$ tends to one, from both directions, the resulting curve approximates the Gompertz function (Gompertz, 1825). The broad physiological interpretation of the parameters and the flexibility of Chapman-Richards function led Pienaar and Turnbull (1973) to the conclusion that it was a "promising basis for a generalized theory of growth and yield". Indeed the function is now widely applied, not just to stand growth but to individual trees and their component parts (von Gadow and Hui, 1999).

### 2.2.2 Data sources

Empirical growth models at all resolutions require information on tree development at either a stand or individual tree level. The variables measured are typically diameter at breast height, height and crown position and dimensions. If volume is to be used as a variable this is generally estimated from other variables because of the difficulty in direct measurement. Repeated observations are required to develop and validate growth models (Hasenauer, 2006) and these can be obtained from permanent, temporary or interval sample plots (von Gadow and Hui, 1994). Permanent plots provide long time series data, generally at individual tree level, and can be used to describe development over age from a wide variety of sites and management situations. Measurement intervals of 5 or more years will help negate the problems of discrepancies in measurement and short term fluctuations in climatic conditions. Temporary plots can be useful in situations where there is little or no long term data available. In this case a large number
of plots of different ages and covering a range of growth and management conditions are assessed and the information combined to replicate time series data. Interval plots fall between these two but involve two measurements after which they may be abandoned. They have the advantage over temporary plots of including real increment but still avoid the long wait for data from permanent plots. The number of plots and measurements to reliably parameterize more complex tree growth models can be considerable, for example 780005 year growth periods from Switzerland and Austria for the MOSES model (Hasenauer, 2006).

### 2.3 Modelling approaches

Both stand and individual tree models use various functions of height and diameter to predict increment (Hasenauer, 2006; von Gadow and Hui, 1999), and also incorporate routines for competition, mortality and regeneration. Hasenauer (2006) identified two conceptual approaches to the elaboration of increment functions: potential dependent and potential independent. In the former a potential is identified and reduced according to some defined limiting factor such as competition (equation 2.4):
inc $=$ potinc $\cdot C R^{a} \cdot\left(1-e^{(b, \text { comp })}\right)+\varepsilon$
where
inc actual five year increment
potinc predefined five year potential
CR crown ratio
comp competition indices
$a$ and $b \quad$ parameters
$\varepsilon$
remaining error components

In a potential independent model actual increment is predicted directly and no upper limit is defined (equation 2.5):
$\ln ($ inc $)=a+b \cdot($ tree $)+c \cdot($ comp $)+d \cdot($ site $)+\varepsilon$
where

| $\ln ($ inc $)$ | $\log$ of growth (h, dbh) <br> tree |
| :--- | :--- |
| set of tree variables |  |
| comp | variables reflecting competition situation of each tree in a stand |
| site | a variable defining site conditions |
| $a, b, c, d$ | species specific co-efficient estimates <br> $\varepsilon$ |
| remaining error component |  |

In the potential dependent approach site variations are taken into account in defining potential increment. In the direct approach site factors are incorporated into the model as part of the set of independent variables.

### 2.3.1 Examples of European growth models

### 2.3.1.1 MOSES

MOSES - MOdeling Stand rESponse - (Hasenauer, 2006) uses the potential modifier approach first developed by Newnham and used as the basis for the model FOREST (Ek and Monserud, 1974). Both potential height increment and potential diameter increment are reduced by competition effects. This reduction takes into account both past and current competition and includes a variable for changing competition. In the functions below the observed variables are expressed relative to potential:

$$
\begin{equation*}
\frac{i d_{o b s}}{i d_{p o t}}, \frac{i h_{o b s}}{i h_{p o t}}=C R^{b_{1}}\left[1-e^{\frac{b_{2}}{c\left(1+b_{3} \cdot \Delta C l\right)}}\right]+\varepsilon \tag{2.6}
\end{equation*}
$$

where
$i d_{o b s}$ and $i h_{o b s}$ observed values of diameter (cm) and height (m)
$i d_{p o t}$ and $i h_{p o t}$ potential values of diameter ( cm ) and height ( m )
CI competition index
$C R \quad$ crown ratio
$b_{1}, b_{2}, b_{3} \quad$ parameters
$\varepsilon \quad$ remaining error

From these basic functions the model can be used to derive tree volumes, assortments and other information of use to foresters. The height function is based on yield tables on the general observation that within a forest stand management has little effect on height growth and dominant height is similar across a wide range of management scenarios for any given site type. Potential height increment is estimated from regional site index functions developed for Austrian stands using height increment development of dominant trees. Height prediction is independent of stand age though it does rely on known age relationships as used in the site index function. There is an assumption that dominant height and its development represents the actual potential within a stand. Crown ratio is used as a measure of past competition. CI is a measure of current competition.

In early model development diameter was derived from the height functions. In later elaborations use was made of open grown trees (Hasenauer, 1997, 2006; Dash, 2006). It is assumed that within a stand the true potential diameter of a tree cannot be achieved because of competition effects whereas open grown trees are able to reach their
potential diameter and these are used to develop the diameter increment model. There is then an assumption that open grown tree diameter can be related to stand height growth through a height diameter curve. Potential diameter increment is then modified in a similar way to height potential increment.

The model also updates crown ratio using a dynamic model in which the change in height to live crown is a function of height, crown ratio, competition and diameter. There is the possibility of introducing bias in this as both crown ratio and competition are used to model diameter and height. Mortality is modelled using a probability function.

Hasenauer addresses the problem of potential bias in his system of equations by using simultaneous estimation techniques (Hasenauer et al., 1998). The argument here is that this type of model is a system of equations that may not be independent and the calibration of one function may be influenced by any other function in the system. Simultaneous estimation of parameters reduces the possibility of bias.

### 2.3.1.2 PrognAus

PrognAus (Prognosis for Austria) is an example of the potential independent approach and at its core consists of a distant independent, individual tree basal area increment model (Monserud and Sterba, 1996). As with MOSES the models are independent of age, a desirable attribute of models intended for use in uneven aged silviculture (Hasenauer, 2006).

The basal area increment model is a log-linear function:
$\ln \left(B A I_{5}\right)=f(D B H, C R, B A L, C C F$, elevation, slope, aspect, thickness of F-humus and H-humus horizon, soil depth, relief, soil moisture, vegetation type, soil type, growth district)
where:
$B A I_{5} \quad$ basal area increment of a 5 year period $\left(\mathrm{m}^{2}\right)$
DBH diameter at breast height (cm)
$H \quad$ total height (m)
$C R \quad$ crown ratio
$B A L \quad$ basal area in larger trees $\left(\mathrm{m}^{2}\right)$
CCF crown competition factor

The height increment model is a simple linear one:

$$
\begin{equation*}
i h_{11}=f\left(D B H, H, i d_{11}\right) \tag{2.8}
\end{equation*}
$$

where
$i h_{11} \quad$ height increment of an 11 year period
$i d_{11}$ diameter increment of an 11 year period
Also included are a static crown ratio model, mortality model (Monserud and Sterba, 1999) and an ingrowth model.

### 2.3.2 Tyfiant Coed

The primary focus of the Tyfiant Coed model is on volume in order to minimise error propagation (Pommerening and Wenk, 2002). The driving factors for the estimation of the growth parameter $c_{1}$ are the diameter at breast height ( dbh ) of a given tree and a variable, DBHratio. The latter is found from a competition index based on the ratio of the target tree's dbh with that of its most vigorous competitor. The steps to calculate relative volume increment are given by equations (2.9) to (2.11). Once volume has been estimated the model can then be used to estimate both height and diameter at breast height. The model is described in greater detail in section 2.5 .

The growth parameter $c_{1}$ is derived from the ratio of a tree's dbh to that of its primary competitor using equation (2.9):

$$
\begin{equation*}
c_{1 i, t}=\frac{a}{1-e^{\left(-\frac{x \cdot D B H r a t i o t, t}{b+1}\left(\frac{D B H H_{t, t}}{10}\right)^{n+1}\right)}} \tag{2.9}
\end{equation*}
$$

where
$i \quad$ index for tree under study
$a, b, x \quad$ tree species specific coefficients
DBH diameter at breast height ( cm )
DBHratio ratio of DBH of the tree under study and that of its corresponding primary competitor
$t$ current forecast year.

The parameter $c_{2}$ is estimated from $c_{1}$ using the linear function in equation (2.10):
$c_{2 i, t}=c+d \cdot c_{1 i, t}$
where
$c, d \quad$ tree species specific coefficients.
The relative volume increment can now be calculated for the next ten years using equation (2.11):
$\left.p_{i, t+\Delta t}=e^{-c_{1}, i_{i}\left(1-e^{-22, i, i t}\left(1-e^{-0.4 t i}\right)\right.}\right)$
where
$p_{i, t+\Delta t} \quad$ relative increment over time period $\Delta t$
$t_{\mathrm{i}}^{\prime} \quad$ transformed tree age from equation (2.12)
$\frac{\text { tree }^{\text {age }}}{i, t}-10$

### 2.4 Wenk's modelling approach

2.4.1 Relative volume increment and growth multipliers

In Wenk's modelling approach (Wenk, 1969) the future value of a growth quantity, $Y$, is estimated from the current value using a growth multiplier:
$Y_{t+\Delta t}=M Y_{t}$
where
$Y_{t} \quad$ is any growth quantity such as dbh , height or volume at time $t$
$\Delta t \quad$ is the growth period
$M \quad$ is the growth multiplier

The multiplier can be derived from observed increment from long term sample plots or stem analysis data and can be expressed in terms of relative growth rate, $p_{Y}$, based on the value of $Y$ at time $t+\Delta t$ :
$M=\frac{1}{1-p_{Y}}$

This relationship derives from the fact that increment, $I_{Y}$, is the difference in value of the growth quantity at different times and also the product of the growth quantity and relative increment as expressed in the following two equations:
$I_{Y}=Y_{t+\Delta t}-Y_{t}$
$I_{Y}=Y_{t+\Delta t} \cdot p_{Y}$

Equating (2.14) and (2.15) gives:
$Y_{t+\Delta t}-Y_{t}=Y_{t+\Delta t} \cdot p_{Y}$
equation (2.17) can be rearranged to give:
$Y_{t+\Delta t}=Y_{t} \cdot\left(\frac{1}{1-p_{Y}}\right)$

Equation (2.18) is equivalent to equation (2.14) and Wenk defined the term $\left(\frac{1}{1-p_{Y}}\right)$ as the growth multiplier, $M$.

### 2.4.2 Gompertz function

Volume increment is the first derivative of a growth function and there are several that could be used to give values of relative increment. Wenk chose to use a modified version of the Gompertz function (Gompertz, 1825) which has been used in many disciplines to model growth (Wenk et al., 1990). The basic form of this function is:
$Y=a e^{-b e^{-c t}}$
where
$a \quad$ maximum value of growth quantity $Y\left(Y_{\max }\right)$
$b, c \quad$ parameters

The first derivative of the function is:
$\frac{d Y}{d t}=Y b c e^{-c t}$
and relative increment is:

$$
\begin{equation*}
\frac{d Y}{d t} \cdot Y^{-1}=b c e^{-c t} \tag{2.21}
\end{equation*}
$$

Wenk et al. (1990) describe the use of a two parameter version of the Gompertz function. One of the parameters fixes the maximum value of the growth quantity and the second describes the rate of growth. This is achieved by equating $b$ with $c^{-1}$ in equation (2.19) which becomes:
$Y=Y_{\max } \cdot e^{-\frac{1}{c} e^{-c t}}$

Relative increment is now:
$p_{Y}=e^{-c t}$

Wenk and his colleagues found that this function could adequately model tree volume growth for stands in excess of 50 years of age but tended to underestimate growth for younger ages. The function also exhibits some fixed properties which render it rather inflexible when fitting it to empirical data. The inflexibility is due to the fact that the value of the growth quantity at the point of inflexion, i.e. the time of maximum current annual increment, is always a fixed percentage of the maximum value and is about $37 \%$ as shown below:

$$
\begin{equation*}
Y_{\mathrm{t}_{\mathrm{w}}}=\frac{Y_{\max }}{e}=Y_{\max } \cdot 0.368 \tag{2.24}
\end{equation*}
$$

where
$t_{w} \quad$ time at which the point of inflexion occurs
The time at which the point of inflexion occurs is also fixed:
$t_{\mathrm{w}}=-\frac{\ln c}{c}$

The parameter $c$ can also be interpreted and is the relative volume increment at time of culmination (the point of inflexion) which can be shown by substituting (2.25) into (2.23):

$$
\begin{align*}
& p_{Y_{t_{w}}}=e^{-c-\frac{\ln (c)}{c}}  \tag{2.26}\\
& p_{Y_{t_{w}}}=e^{\ln (c)}  \tag{2.27}\\
& p_{Y_{t_{w}}}=c \tag{2.28}
\end{align*}
$$

Wenk surmised that one reason why the Gompertz function did not model early growth so well was that the growth parameter, $c$, took several years to reach its potential value (Wenk et al., 1990). To overcome this and increase the flexibility of the model two more parameters were introduced into the function for relative volume increment (Wenk, 1969). The growth parameter, designated $c_{0}$ in equation 2.29 , increases at a rate proportional to its value until its potential is reached and the additional parameters control this rate:
$\frac{d c_{0}}{d t}=c_{2}\left(c_{1}-c_{0}\right)$
where
$c_{1} \quad$ is the maximum value of $c_{0}$
$c_{2}$ controls the rate at which $c_{1}$ reaches its potential
equation 2.29 can be integrated to give:
$c_{0}=c_{1}\left(1-e^{-c_{2}}\right)$
and the function for relative volume increment is now:
$p_{Y}=e^{-c_{1} i\left(1-e^{-c z i}\right)}$
where
$t^{\prime} \quad$ transformed age (section 2.4.5)

An even better fit could be obtained by introducing a third parameter which allows $c_{2}$ to vary in a similar way to $c_{l}$ and relative increment becomes:


Equation (2.32) has been found to give a good fit to empirical data for ages up to 100 years but beyond this time further flexibility is again required. This was introduced using a fourth parameter which, depending on its value, has little effect in the early growth stages but can enhance or suppress growth at older ages (Wenk, 1979, Nake, 1983). Relative increment is given by:


The main parameter, $c_{1}$, accounts for the overall shape of the growth curve which is modified in the early years by parameters $c_{2}$ and $c_{3}$. The influence of $c_{2}$ and $c_{3}$ lasts only for 50 to 60 years beyond which only parameter $c_{1}$ is necessary to describe relative volume increment over time. Beyond age $100 c_{4}$ further modifies the growth pattern. Parameters $c_{1}, c_{2}$ and $c_{3}$ are always positive. Parameter $c_{4}$ can take positive or negative values and if set to zero the function behaves as if it had only three parameters. The effects of the various parameters on relative volume increment and volume growth are described in the next sections.

### 2.4.3 Response to parameters

For a given initial condition $c_{l}$ defines the shape of the growth curve and is itself dependent on tree species, site quality and silvicultural treatment. Under constant conditions the growth parameter $c_{l}$ remains constant. There is an inverse relationship between $c_{1}$ and relative volume increment $\left(p_{\mathrm{V}}\right)$ and lower values of $c_{1}$ have been equated with increased tree vigour (Pommerening and Wenk, 2002). The function of relative increment is shown in Fig. 2.2 for two different values of $c_{1}$. The effect of
introducing parameters $c_{2}$ and $c_{3}$ is also illustrated. It can be seen that $c_{2}$ and $c_{3}$ effectively raise the value of $p_{\mathrm{V}}$ at any given age up to an age of approximately 60 years. If either $c_{2}$ or $c_{3}$ take higher values than 1.0 and 0.4 , respectively, then the convergence of the curves would occur sooner and this is illustrated in Fig. 2.3.


Figure 2.2 Effect of $c_{1}, c_{2}$ and $c_{3}$ on relative volume increment. The limit curve refers to the basic Gompertz function, equation 2.23. For the three parameter function, equation 2.32, $c_{2}=1.0, c_{3}$ $=0.4$. By 60 years of age there is less than 0.005 difference between the values of $p_{V}$ for each pair of equations.


Figure 2.3 Effect of $c_{2}$ on relative volume increment for $c_{1}=0.2$ and $c_{3}=0.4$. The limit curve refers to the basic Gompertz function, equation 2.23.

It is clear from Figs. 2.2 and 2.3 that $c_{2}$ and $c_{3}$ have the effect of increasing and sustaining relative volume increment in the early years of growth. The magnitude of this effect and the duration are determined by the values of the parameters. The lower the value of $c_{2}$ the greater is relative volume increment for any given year. As $c_{2}$ increases then the relative volume increment function tends towards the limit curve and merges with it at a much earlier age. Alterations in the value of $c_{3}$ have a similar effect.

The effect of the different parameters on volume development is illustrated in Figs. 2.4 and 2.5. A low $c_{1}$ appears to indicate increased vigour and, for any given starting volume, final volume will be much greater than if $c_{1}$ values were higher. Higher values of $c_{2}$ and $c_{3}$ result in lower final volume for any given value of $c_{1}$ and the same starting volume.


Figure 2.4 Individual tree volume development for different values of $c_{1}$. Starting volume $0.2 m^{3}$ at age 20.


Figure 2.5 Volume development for different values of $c_{2}\left(c_{1}=0.2\right)$; starting volume as for figure 2.4.

### 2.4.4 Increment period

The function for relative volume increment provides an instantaneous value for any given time. Parameters for the Wenk model can be estimated from empirical values of $p_{\mathrm{V}}$ from stand or stem analysis data using equation (2.34):
$p_{V}=\frac{V_{t+\Delta t}-V_{t}}{V_{t+\Delta t}}$
where
$p_{V} \quad$ relative volume increment
$V_{t} \quad$ volume $\left(\mathrm{m}^{3}\right)$ at time $t$
$\Delta t \quad$ interval period
Any time period can be used when assessing increment but a period of 10 years has been found to give the best combination of resolution and reliable results (Wenk et al., 1990). This time length is sufficient to take account of measurement errors, short term climatic fluctuations and random effects that might otherwise mask the overall growth pattern.

As $\Delta t$ tends to zero then $p_{\mathrm{V}}$ tends to the current relative increment. For larger values of $\Delta t$ there will be an element of bias in the result and the value of $p_{\mathrm{V}}$ tends to be underestimated prior to culmination and overestimated after it. This is partly because of the length of the increment period but also because the values of the growth quantity at the end of the period are used to calculate $p_{\mathrm{V}}$ whereas the theoretical value should be approximately midway between the beginning and end of the growth period (Fig. 2.6). The smaller the time period over which increment is measured the more accurate will be the estimate of the rate of growth. This is partly compensated for by the use of transformed time (section 2.4.5). Figs. 2.7 and 2.8 illustrate the effect on the increment and relative increment curves.


Figure 2.6 Bias in estimation of relative increment. The black point is the point of inflexion and the solid and broken line represent increment periods of 10 years.


Figure 2.7 Difference in the theoretical (solid line) and empirical (broken line) relative increment curves.


Figure 2.8 Difference in theoretical (solid line) and empirical (broken line) values of increment.

Figs. 2.7 and 2.8 are based on the Gompertz function (equation 2.21 ) with a potential maximum value of $Y$ of 100 and a value of the parameter $c$ of 0.25 . Volume is calculated directly from the Gompertz function and dy/dt from the first derivative. Increment is volume at year $t+1$ less volume at year $t$. If a multiplier were derived from theoretical $p_{\mathrm{V}}$ values then final volume would be grossly overestimated if the starting value were true value at age 1. If empirical values were used final volume would be underestimated. If $c_{1}$ is calculated from the empirical values of $p_{V}$ then they are found to vary and, in this case, never quite match true $c_{1}$ value. This has implications for interpretation of $c_{1}$ estimated from one increment measurement.

### 2.4.5 Age transformation

The Gompertz function can adequately describe the growth pattern of many organisms. However trees have very long lifespans and continue to grow throughout their lives and very small parameter values are needed to adequately model many tree species growing in north temperate climates. In order to improve efficiency in modelling volume of trees Wenk (1979) applied a transformation to tree age which artificially reduces the long life span of trees. This effectively accelerates time and parameterisation of the function is improved.

Transformed age is given by:
$t^{\prime}=\frac{t-x}{x}$
where
$t$ tree age
$x$ any convenient time interval

The effect of transforming age is illustrated in Fig. 2.9. One time unit in the function now represents a period equal to $x$ years and the model can only be parameterised from age $x$ as before this transformed age would be negative. In most instances $x$ is set to equal 10 but can be as little as 2 for faster growing species (Haufe, 2001). Wenk (1998) used $\mathrm{x}=2$ for Pinus massoniana in Vietnam and it is possible that some faster growing species in temperate zones could be modelled more effectively with values of $x$ less than 10. Parameters obtained using different time transformations cannot be compared directly as the value of $x$ affects the value of $p_{V}$ at any given age and, therefore, the value of $c_{1}$. When the growth period is the same as the transformation period the reference age used to calculate relative increment is shifted to to the beginning of the increment period rather than the end.


Figure 2.9 Effect of transforming age. For a period of $x=10$ years only 19 units of time are required to cover a total age of 200 years.

### 2.4.6 Estimating annual values of the growth multiplier

Function 2.24 is designed for use with 10 year intervals and therefore when analysing data reported for any other time period, for example annual volume increment of stem analysis trees, they must first be converted to ten year periods. The multipliers obtained from the analysis are also for ten year periods even though they may be reported in annual time steps. It is possible to introduce more precise and flexible updating of increment by interpolating annual multipliers from ten year values.

A typical averaging technique was reported by Gerold and Römisch (1977) and is shown below:
$p_{V 1}=\left(1-\sqrt[10]{\frac{p_{V 10}}{100}}\right) \cdot 100$
where $p_{\mathrm{V} 1}$ and $p_{\mathrm{V} 10}$ are annual and ten year relative increment values respectively.

A problem with this approach is that negative bias is immediately introduced into the volume calculation which is only rectified at the end of the ten year period. This is because the annual multipliers are constant throughout the 10 year period and are initially lower than the true multiplier. At the end of the period they are higher than the true value.

To improve the estimation of annual multipliers Gerold and Römisch (1977) developed a more sophisticated interpolation technique. Bias is reduced, and the annual multipliers can be used to estimate multipliers for any other period of interest. To work efficiently this technique relies on the fact that over time $p_{\mathrm{V}}$ tends to zero and the multiplier therefore tends to one. The interpolation is outlined below.

Volume for any time in the future $\left(V_{t+n}\right)$ can be determined from current volume $\left(V_{t}\right)$ by multiplication (using multipliers, $M_{l^{+} / 0}$ etc.) in ten year time steps:

$$
\begin{equation*}
V_{t+n}=V_{t} \cdot M_{t+10} \cdot M_{t+20} \cdot M_{t+30} \cdot \ldots \cdot M_{t+n} \tag{2.37}
\end{equation*}
$$

Future volume can also be calculated from volume in the following year:
$V_{t+n+1}=V_{t+1} \cdot M_{t+10+1} \cdot M_{t+20+1} \cdot M_{t+30+1} \cdot \ldots \cdot M_{t+n+1}$
and because $p_{\mathrm{V}}$ tends to zero and the multiplier tends to one:
$V_{t+n} \rightarrow V_{1+n+1}$
therefore:
$V_{t} \cdot M_{t+10} \cdot M_{t+20} \cdot M_{t+30} \cdot \ldots \cdot M_{t+n} \rightarrow V_{t+1} \cdot M_{t+10+1} \cdot M_{t+20+1} \cdot M_{t+30+1} \ldots \cdot M_{t+n+1}$
therefore:
$\frac{V_{t+1}}{V_{t}}=\frac{M_{t+10} \times M_{t+20} \times M_{t+30} \times \ldots \times M_{t+n}}{M_{t+10+1} \times M_{t+20+1} \times M_{t+30+1} \times \ldots \times M_{t+n+1}}$

Which is the annual multiplier:
$\frac{V_{t+1}}{V_{t}}=M_{t+1}$

To summarise the annual multiplier is:
$M_{t+1}=\frac{\prod_{j=1}^{n} M_{t+j 10}}{\prod_{j=1}^{n} M_{t+j 10+1}}$

With increasing $n$ the quotient $M_{t+j 10} / M_{t+j 10+1}$ approaches one and the estimate of the annual multiplier becomes constant. It is therefore convenient to limit $n$ by defining a threshold value for the quotient, e.g. 1.0001.

For forecasting intervals other than 10 or 1 year the correct multiplier can be determined from:

$$
\begin{equation*}
M_{t+n}=\prod_{j=1}^{n} M_{t+j} \tag{2.44}
\end{equation*}
$$

### 2.4.7 Expected parameter values

The model approach can be applied to whole tree populations and to individual trees. For individual trees it has been shown that $c_{l}$ is negatively correlated with relative volume increment and assumed that lower values of $c_{1}$ imply increased tree vigour. However when modelling populations of trees, for example stand development, this latter relationship is reversed (Wenk et al., 1990). This is seen in the fact that for stand data higher $c_{l}$ values are positively correlated with volume production, i.e. greater volume production occurs in stands with lower relative volume increment.

The relationship between $c_{1}$ and stand productivity can be illustrated by examining volume increment given in yield tables. The timing of culmination should give an indication of the value of the growth parameter given the fixed properties of the Gompertz function discussed earlier (section 2.4.2). In Fig. 2.10 periodic increment for different yield classes of Sitka spruce from yield tables (Edwards and Christie, 1981) is shown. Approximate values of $c_{1}$ (derived from the limit curve) are related to approximate yield class in table 2.1 along with time of culmination. These data illustrate and emphasise the point that $c_{1}$ is positively correlated with yield class and do
suggest potential limits, and pattern of variation, for the growth parameter for stands in British conditions.

Table 2.1 Values of $c_{1}$ matched to the time of peak periodic increment ( $t_{\text {culm }}$ ) from yield tables (Edwards and Christie, 1981). Note YC10 data seem anomalous.

| YC | $t_{\text {culm }}$ | $c_{1}$ |
| :--- | :--- | :--- |
| 24 | 39 | 0.355 |
| 22 | 41 | 0.345 |
| 20 | 43 | 0.335 |
| 18 | 45 | 0.325 |
| 16 | 47 | 0.315 |
| 14 | 49 | 0.305 |
| 12 | 51 | 0.295 |
| 10 | 55 | 0.290 |
| 8 | 54 | 0.285 |
| 6 | 55 | 0.280 |



Figure 2.10 Periodic increment of unthinned Sitka spruce from yield tables. Data are for the tree with mean basal area and the period is five years. Yield class from 6 (lower curve) to 24 (upper curve) in steps of 2 . Open circles are the approximate time of culmination.

Within a stand the negative relationship between vigour and $c_{1}$ value is likely to hold, but now competition is the limiting factor. The smaller, more suppressed trees have lower relative increment and therefore higher $c_{1}$ values. The relationship between stand $c_{1}$ and within stand $c_{1}$ is illustrated in Fig. 2.11.

In Fig. 2.11 the larger tree represents the potential of a higher yield class site. The smaller tree could be of the same age but from a lower yield class or a smaller tree from the same yield class. Trees of similar age and volume, but from different site types could have different $c_{1}$ values ( $c_{1 \mathrm{~A}}$ and $c_{1 \mathrm{~B}}$ in Fig. 2.11). This could occur if starting volume and/or $c_{2}$ and $c_{3}$ values were different. The diagonal line rising to the right is $c_{1}$ value plotted against yield class. The two L shaped curves indicate individual tree $c_{1}$ within the stand. It can be seen that within a stand there are a wide range of sizes with similar $c_{l}$ values but that the latter gradually rises as trees get smaller. At some point there is a more rapid rise in $c_{l}$ value probably associated with suppression and mortality.


Figure 2.11 Relationship between tree size and $c_{1}$ within and between different site types.

Clearly there is no simple relationship between relative increment and absolute size of an individual tree and it is important to understand the context in which values of $c_{1}$ are quoted: at stand level or individual tree level.

### 2.4.8 Allometry

Typically in growth models volume is derived from other measures of tree growth such as diameter, basal area, height and form factors (Philip, 1994). The Wenk approach models volume directly using the functions previously described and estimates height and diameter through allometric principals (Wenk, 1978, 1994). Allometric relationships describe the way a growth quantity of a given organism grows relative to another, for example the limbs of a child grow at different rates to that of the body (Niklas, 1994, Reiss, 1989). Such relationships have been used widely in growth studies and were first applied in forestry in the 19th century. Their usefulness was first described in Britain by Huxley (Huxley, 1932). The allometric relationship can be expressed as:

$$
\begin{equation*}
y=x^{b} \tag{2.45}
\end{equation*}
$$

Where $y$ and $x$ are different growth quantities of the same organism and $b$ is the allometric coefficient describing the relationship between them.

Provided the growth quantities are measured in the same dimensions, if $b$ is greater than one then $y$ is growing at a faster rate than $x$, (positive allometry) and at a slower rate if $b$ is smaller than one (negative allometry). In the context of forestry an allometric coefficient of 3 would represent isometric growth between diameter and height growth and volume growth because of the different measurement units involved.

In applying allometry to tree growth it is useful to consider the general relationships between volume, basal area $(g)$, height $(h)$ and form factor $(f f)$ :
$V=f(g, h, f f)$
where basal area is a function of diameter $(d)$ squared so that:
$V=f\left(d^{2}, h, f f\right)$

The absolute quantities can be replaced by relative growth rates and the corresponding multipliers:

$$
\begin{equation*}
p_{V}=f\left(p_{D^{2}}, p_{H}, p_{F}\right) \tag{2.48}
\end{equation*}
$$

or
$M_{V}=f\left(M_{D^{2}}, M_{H}, M_{F}\right)$

Wenk (1969) established an allometric relationship between volume growth rate and height growth rate:
$\left(1-p_{V}\right)=\left(1-p_{H}\right)^{m}$
this can be rearranged to give:
$\left(1-p_{H}\right)=\left(1-p_{V}\right)^{\frac{1}{m}}$
or in terms of the multipliers
$M_{H}=M_{V}{ }^{\frac{1}{m}}$

Using this relationship height development is now also controlled by the parameters of the growth function through the allometric coefficient. As with the volume multiplier relative growth rates are based on values at time $t+\Delta t$.

The multiplier for diameter growth can also be expressed in terms of the multiplier $M$.

If equation (2.49) is rearranged we get a diameter function:
$M_{D^{2}}=f\left(M_{V}, M_{H}{ }^{-1}, M_{F}{ }^{-1}\right)$
and
$M_{D}=f\left(M_{V}^{\frac{1}{2}}, M_{H}^{-\frac{1}{2}}, M_{F}^{-\frac{1}{2}}\right)$
but
$M_{V}=M_{H}{ }^{m}$
and so

$$
\begin{equation*}
M_{D}=f\left(M_{H}^{\frac{m}{2}}, M_{H}^{-\frac{1}{2}}, M_{F}^{-\frac{1}{2}}\right) \tag{2.56}
\end{equation*}
$$

which if rearranged gives

$$
\begin{equation*}
M_{D}=f\left(M_{H}^{\frac{m-1}{2}}, M_{F}^{-\frac{1}{2}}\right) \tag{2.57}
\end{equation*}
$$

which in Pommerening (2005) is expressed as

$$
\begin{equation*}
M_{d, i, t+\Delta t}=\frac{M_{f, i, t+\Delta t} \frac{-1}{2}}{M_{h, i, t+\Delta t} \frac{-m_{, t+\Delta \Delta+1}^{2}}{2}} \tag{2.58}
\end{equation*}
$$

### 2.5 Site dependent modelling

Understanding the relationship between forest growth and site conditions is important for a number of reasons. The forester is interested in tree species suitability and the productive capacity of a site as well as opportunities and limitations regarding silvicultural practice and management. However there is now wider concern for sustainable land use (UKWAS Steering Group, 2000; Forestry Commission, 2004), which has continued to raise both professional and public awareness of the interactions between commercial forestry and wider ecological issues. Although foresters have long considered the problem of sustainability from a commercial point of view, there has been a conceptual shift that now considers the sustainability of the land itself rather than that of the trees which grow on it. Added to all this are continued concerns regarding the effects of climate change (Broadmeadow, 2002) and also continued shifts in public perception and preferences regarding the use to which forest land is put. This has influenced the debate on forest management, and in particular the role that continuous cover forestry has to play in countries where clearfell systems have been the dominant form of silvicultural practice (Forestry Commission, 2001; Pommerening and Murphy, 2004). The idea of sustainability goes beyond mere productivity to consideration of the conservation and management of the site and all that that involves.

There is, therefore, increased or perhaps renewed awareness of the importance of site conditions and their influence on tree growth and land management. In fact the importance of site and sustainability has long been recognised, as a glance at older texts will indicate (Schlich, 1904; Nisbet, 1905), and much work has been done, over many decades, in an attempt to link site factors to productivity (Carmean, 1975).

Several objectives require information at different levels of detail on the relationship between site conditions and tree growth e.g. estimation of timber productivity, development of criteria and indicators for land quality and sustainability and complex systems of classification for multi-purpose land use. Although the requirements for these objectives may differ there are areas of common ground. One common goal is to find environmental measures which are easily observed and measured and which correlate with tree growth.

### 2.5.1 Site conditions and tree growth

The basic requirements of tree growth are light, warmth, nutrients and moisture. The availability of these is the product of complex interactions between a wide range of environmental and other factors that are in general terms, well understood (Kimmins, 1996). Factors affecting tree growth can be placed into one of three broad categories, viz. climate, physiography and soil. In addition there are competition effects and the genotype of the tree is also important though trees can adapt to site conditions in a relatively short space of time (Peterken, 2001). Detailed analysis of the effect on tree growth of these factors is complicated by the interactions between them and also interdependence between them and the trees. Although foresters may intuitively develop an understanding of these relationships there have also been many attempts to quantify them to improve both understanding and management practice (Coile, 1952; Ralston, 1964; Carmean, 1975; Hägglund, 1981; Skovsgaard and Vanclay, 2008). A major problem is that the processes which directly affect growth may not be easy to identify or quantify and indirect measures may have to be used. Ideally these should also be simple and inexpensive to assess and highly correlated with forest productivity (Moffat, 2003). However, the best models have only been able to explain up to about $80 \%$ of variation in tree growth and "different environmental factors will prove useful in different regional and local forest ecosystems" (Barnes et al., 1998).

### 2.5.2 Site Quality

Site quality can be defined as the "innate productive capacity of the land area involved" (Schönau, 1987). Under this definition the better the land the more productive it is. It is a wide definition, production being that of all living matter: flora and fauna, above and below ground. The commercial forester requires a narrower definition and in the context of timber management site quality is "the timber production potential of a site for a particular species or forest type" (Schönau, 1987). Site quality can be evaluated by measuring past production, a straightforward approach which works relatively well in agriculture but becomes more complicated in forest systems not least because it takes many years from planting to final harvest of the crop (Clutter et al.,1983). An additional problem is the definition of productivity. According to Philip (1994), of greatest usefulness to foresters is the commercial volume of the tree, i.e. of the tree stem, usually measured to a minimum diameter. For practical reasons wood content, remains the best
known measure of productivity. However, the measurement of tree volume is laborious, time consuming and costly and stand volume is dependent on stand density and management history. Therefore alternative measures of productivity have been sought.

Many different approaches have been used to assess productivity or site quality. They can generally be described as either direct or indirect (Clutter et al., 1983). Direct methods are measurements of the trees themselves and strictly speaking of actual volume.

1. Estimation from historical yield records.
2. Estimation based on stand volume data.
3. Estimation based on stand height data.

Indirect methods estimate yield from other factors that have been empirically related to yield. Estimates based on stand height should be included in this category (Vanclay, 1994).

1. Estimation from overstory interspecies relationships.
2. Estimation from lesser vegetation characteristics.
3. Estimation from topographic, climatic and edaphic factors.

Vanclay (1994) distinguished between phytocentric and geocentric approaches to site productivity estimation which can use either direct or indirect measures. The direct phytocentric approach is that which measures wood volume production and is invariably better than indirect ones (Clutter et al., 1983). In theory it is expected that the same site would produce the same amount of wood as long as it is fully occupied regardless of density. However, yield is conditioned by genetic and site factors, by age of rotation, stand history and stand density. Direct phytocentric methods also require the existence of the species of interest now or in the recent past and are laborious and time consuming to carry out, generally requiring detailed monitoring of harvesting or measurement of long term sample plots. A great deal of work, therefore, has gone into the development of indirect methods of site quality estimation.

The problems of measuring volume directly has lead to the use of surrogate measures, of which site index (SI, see section 2.5.3) is a phytocentric approach which is largely independent of stand density and is now almost universally adopted as a measure of site quality (Barnes et al., 1998). The use of site index can present problems (Vanclay,

1994; Fisher and Binkley, 2000) and some of these are discussed below. Geocentric approaches concentrate on the site itself rather than the stand and estimate site productivity from measures of environmental variables. Some of these variables can be measured directly but it may not be easy or convenient to do so and, again, indirect measures are used as surrogates for these. There are numerous ways of relating site variables to productivity and there remain many complex issues to be addressed. One of these is the way in which site is related to volume production and this is often done through site index, an irony which is not missed by Vanclay (1994).

### 2.5.3 Site index

Site index is a measure of site quality that is generally given in terms of height at a given reference age. It is an indirect measure of productivity and traditionally has been the most widely accepted estimate of it, having been initially used in the $19^{\text {th }}$ century (Tesch, 1981). Numerous texts describe the theory and development of site indices e.g. Clutter et al. (1983), Philip (1994), Vanclay (1994) and van Laar and Akça (1997). Site index is useful because it has been found that tree height is positively correlated with productivity and, for many temperate tree species, unlike volume, it is little affected by stand density and management history. To be of use to managers, however, the second step of relating index to volume production still has to be taken and yield tables have been developed that show these relationships (van Laar and Akça, 1997). In some countries volume production expressed as maximum mean annual increment (MAI) is the preferred method of expressing site quality, though this is still found from height age relationships given in yield tables (Edwards and Christie, 1981; Schönau, 1991).

The estimation of site index requires information on the age and height of the stand. The best sources of these data are long term sample plots. Alternatively stem analysis can be used. Height has been defined in several different ways but is generally taken to be the average height of dominant and co-dominant trees. Such trees can be difficult to identify and measure and top height is frequently used as a more objective measure (Wang, 1998; Mailly et al., 2003). Top height is the average height of the 100 trees per hectare of largest dbh (Helms, 1998). Age can also be difficult to determine, if planting date is not known, and an alternative is to use breast height age, a measure frequently used in Canada (Carmean et al., 2001). Another advantage of breast height age is that it avoids the early years of tree growth when factors other than site often have greater influence
on the tree. Clutter et al. (1983) points out that a reference age is not a fundamental concept in expressing site quality and describes a method for labelling height curves by percentiles. An alternative approach to SI estimation is the growth intercept method which measures the internode distance on tree boles and averages growth over the middle part of the tree's life when it is more or less constant (Wakely and Marrero, 1958; Carmean, 1975; Site Productivity Working Group, 2000).

Van Laar and Akça (1997) provide a brief description of the use of SI curves and present many examples. Site index curves regress stand height over age and provide an estimate of height at a standard age (Barnes et al., 1998). In the past a single guide curve was developed from all data and additional curves were harmonised to this, i.e. a family of anamorphic curves was developed (Clutter et al., 1983). It is assumed that the growth curve is the same for all sites with no account taken of site factor effects on growth. It is also assumed that site differences are apparent at an early age. The weaknesses of this approach are well known (Fisher and Binkley, 2000), perhaps the main ones being that they may not represent actual stand growth accurately and the assumption that growth patterns are the same on all site types. Even where two site types have the same index, growth patterns may not be the same and height growth patterns vary both regionally and locally. Therefore, polymorphic curves which take account of these variations are to be preferred (Clutter et al., 1983; von Gadow and Hui, 1999). Research work continues into the effect of site factors on height growth and the development of polymorphic site index curves (Carmean, 1975; Monserud and Rehfeldt, 1990; Wang et al., 1994; Splechtna, 2001). Site index curves have generally been developed for individual species but in Germany and parts of the USA they have also been applied to mapped ecosystem types for intensive forest management (Barnes et al., 1998).

Vanclay (1994) regards site index as a temporary solution to the difficult problem of solving a geocentric approach to productivity. However, he believes that it is now seen as the solution to the problem and that foresters now talk of direct and indirect methods of site index estimation, a situation he regards as unhealthy. Fisher and Binkley (2000) point to the empirical nature of SI which may be determined to the nearest 30 cm 60 cm from curves with confidence intervals of $>1 \mathrm{~m}$. These values are then compared to other methods of evaluation to determine their accuracy. Difficulties in procedures and
interpretation are also discussed by Garcia (2004), and Stearns-Smith (2001) emphasises the importance of understanding how the site index for any given site was derived.

Despite these difficulties Fisher and Binkley (2000) describe site index as a "troubling but preferred way to measure site quality" and in North America it remains the standard against which all other forms of site evaluation are measured. The approach must be applied with caution, however, even though curves can be developed for ecosystem types or groups of ecosystems. Also, in cases where the site index for a certain species cannot be determined directly, alternative methods of estimating site index are required to estimate forest productivity. For example, alternative methods are required in situations where the species of interest is absent, is too young or too old for site index calculations, or has suffered mechanical or pathogenic damage (Kayahara and Pearson, 1995). In such cases it may be possible to make comparisons between tree species (Barnes et al., 1998).

### 2.5.4 Plants as indicators of site quality

The use of vegetation as an indicator of site productivity has been popular since the 1920s following the work of Cajander (1926). Daubenmire (1976) was very much in favour of this approach and argued that assessment of the vegetation was the best way of assessing site productivity because, as Coile (1938) also recognised, it reflects the sum of all the elements of the environment important to plants. Daubenmire dismissed criticism of the use of vegetation as an indicator of productivity though floristic systems may only gave satisfactory results in natural or slightly altered forests (Killian,1984). They have potential particularly where there is marked variation in altitude, precipitation and soil and there has been limited human impact on the original vegetation. They are hardly of use in areas with destroyed or disturbed vegetation that has been harvested or burned repeatedly or in intensive agrisystems (including intensively managed plantations of exotic species). Also this approach is of more use in temperate regions where there are few tree species and thus relatively few distinct associations of vegetation.

Barnes et al., (1998) use the term phytometer and note that vegetation can be assessed in a number of different ways. Presence, relative abundance and relative size can all be
used and species considered individually or in characteristic groupings. Other factors do have to be considered such as competition and mutualism, herbivory, low light and previous site history. Also the indicator value of individual species may change with regional climate and physiography. Schönau and Aldworth (1991) also point out that ground vegetation can be used alone or in combination with overstorey species.

The concept of species groups has been recognised for many years but may be restricted in use if key species are missing. In this approach certain groups of ground vegetation are related to tree species and productivity. The underlying assumption is that the ground flora reflects and integrates all other environmental variables into one relatively easy to measure index. This concept worked well in Finland (Cajander, 1926) where there were few associations of vegetation and few tree species to consider. In Canada Krajina and his colleagues have spent decades studying plant-environment relationships and Klinka et al., (1989) have characterised 416 species by four site attributes: climate, soil water, soil nitrogen and ground surface material. These attributes are split into classes and indicator species for an attribute placed into a class giving a total of 20 species groups. Each species can be assigned to a group in one or more of the attributes and any site can then be characterised by reference to the indicator species present. Plants which repeatedly occur together in similar conditions are grouped. All biota can be used and named for the most characteristic species. The groups represent an integrated effect and the individual value of each species may not be discernable. The problem of variation across regions has been noted and a regional classification framework may be of value. Often such groups are not used alone but in conjunction with other factors. In the Western United States plant associations have also been related to habitat types which are defined in terms of late successional vegetation and may have some value in practical land management (Daubenmire 1976). It is assumed that the natural potential climax integrates and expresses the environmental complex for a specific geographical area and is a widely used concept in growth and yield studies (Monserud, 1984; Stage, 1989). Taxonomies can be constructed and keys developed to aid site designation which provides a framework for extensive management of large areas. It should be pointed out that within large areas of habitat type there may be significant differences in physiography and soils due in part to methods of classification (Daubenmire, 1976).

Another approach to site quality assessment is the use of indicator plants. This involves the identification of individual species which are given a score relating them to site productivity. In Europe this work was pioneered by Ellenberg (1988). His values were adapted for use in Britain by Hill et al. (1999) and also by Wilson et al. (2001). Wilson's work provides the basis for estimation of soil nutrient regime in the Ecological Site Classification (Pyatt et al., 2001).

There are limitations to the application of vegetation as a single factor and the following list is not exhaustive (Rowe, 1984).

1. Strong control by macro and micro climate.
2. Sensitivity to disturbance.
3. Floristic complexity, requiring identification of entire component of vascular plants plus mosses and lichens.
4. Dynamic and changing through time.
5. Variable in spatial distribution (importance of sampling).
6. Variable in vertical layering.

Results using only vegetation as an indicator of site quality have been mixed, although Monserud (1984) found a link with site index curves. Anderson (1950) adopted the idea of plant associations in Britain for forestry as did Birse (1980) and Birse and Robertson (1976) for soil associations in Scotland. Vanclay (1994) feels that floristic classification remains imprecise, and soil classification and survey for forestry in Britain were instigated because of the unsatisfactory results obtained through this method (Moffat, 1991).

### 2.5.5 Physiography and site quality

Purely physiographic approaches have also been attempted. Such factors begin to take effect at regional and local site level, modifying the influence of gross climatic factors. This works in part because many factors are related to others. For example, elevation and topographic position are related to climatic factors. Angle of slope, aspect and position have influence on moisture relationships and climatic factors (Stage, 1976; Verbyla and Fisher, 1989; Tyler et al., 1996) and site quality has been assessed using only aspect, slope and position (Meiners et al., 1984; Carmean, 1967; McNab, 1987, 1989).

### 2.5.6 Climatic factors

Climatic factors can provide an approximate indication of production on a regional or altitudinal basis and are more closely related to genetic differences than are soil factors. Temperature and precipitation may be used to compare forest growth in various geographic regions or altitudinal zones assuming similar soil conditions or that soils are related to climate. Within the climatic region growth will depend on physiographic and soil conditions. There tends to be a balance between the number of factors used for precision, and time and cost in measurement. One of the most widely used climatic indices is Paterson's CVP index (Vanclay, 1994). This was designed to be used over large areas to predict maximum growth potential. It is probably useful at large scales but not at a more detailed site or even regional level though it has been correlated with mean annual increment in France (Pardé and Bouchon, 1988). The CVP also indicates that, at a primary level, climate is the main driver of productivity, other factors modifying its effect on a local scale.

There are numerous ways of expressing climatic information. Monthly average temperatures, length of growing season, minima and day degrees above a standard temperature are just a few. As well as this some studies use surrogate measures, and both position (latitude and longitude) and elevation have been found to correlate well with tree growth (Farelly et al., 2002). Rainfall can also be used as either a gross figure or analyzed in shorter periods. Soil moisture deficit is a problematic measure because of the difficulty of measuring evapo-transpiration. Nigh et al. (2004) reviewed the effect of climate on the growth of several species in British Columbia.

Understanding the effect of environmental variables is of importance in the context of climate change (Spiecker et al., 1996; Cannell et al., 1998). Moffat (2003), for example, talks of the double edged sword of nitrogen pollution which potentially leads to increased productivity but also to increased acidification which limits other macro nutrients and ultimately reduces fertility and yield. Increased growth due to increases in atmospheric $\mathrm{CO}_{2}$ could be limited because of increased nutrient demand (Moffat, 2003).

### 2.5.7 Edaphic factors

Edaphic factors have been used to assess site quality independently but also in combination with other factors and can provide further refinement to estimates based on
climate alone. Results of studies have been variable and many findings are both species and site specific. Carmean (1975) reviewed edaphic approaches, listing 41 individual studies. The factors used are generally those that are easy to measure without necessarily having a direct causal link to growth, but Carmean reduced the main factors to those relating to soil moisture regime, soil nutrient regime and aeration. These in themselves are not easily observed or measured.

There is a wide selection of possible measures that can be used to characterise soils and relate them to site quality. Soil morphology and both chemical and physical factors can all be used (Schoenholtz et al., 2000) and Moffatt (2003) listed over 30 physical and chemical properties of soil that might be used for soil quality indicators. Not all of them may be useful in productivity studies but they give an impression of the number of potential variables that could be used. The choice of variables and methods of sampling and measurement requires some care and there are many potential pitfalls. Moffat (2003) discusses some of the problems, which include spatial and temporal variability of soil properties. Some of these are exacerbated in a forestry context due, in the main, to stemflow and root and crown architecture, but also previous crop, wildfire, windthrow, woodland animals and cultivation. Fisher and Binkley (2000) point out that a large proportion of work in soil science has been carried out in an agricultural context and does not transfer well to forestry systems. For example, they claim that "forest soil science has yet to identify generally useful measures of soil fertility which relate to tree response" (Fisher and Binkley, 2000). Soil organic carbon is widely regarded as important for productivity but Nambiar (1996) points to the lack of quantitative data and Grigal (1984) even found a negative relationship. Another commonly used measure of fertility, soil pH , also reveals little direct information and the relationship between yield and pH is less certain in forestry than in agriculture. Moffat (2003) noted the lack of consistency in the reported relationships between tree growth and soil variables, particularly soil fertility, and suggested several possible reasons.

1. Total elemental measures of N and P do not correlate with plant available fraction.
2. Many species are in fact satisfied with supply.
3. Atmospheric supply is adequate.
4. Depletion of nutrients by removal in woody biomass is rare.

Other studies have found positive relationships between foliar nutrient levels, soil nutrient levels and site index (Wang and Klinka, 1997). Dynamic interactions between tree and soil over time are also a complicating factor (Moffat and Boswell, 1990) and Page (1967) attempted to take some of these factors into account when investigating site/productivity relationships in North Wales. Some properties may stabilise while others are more cyclical (Moffatt, 2003). A better understanding of these processes may provide a key to improved prediction of productivity. The position within the soil from where trees derive nutrients may change with time, and trees are also capable of utilising their own stored supplies (Gilmore et al., 1968). Effective rooting depth may be the most influential predictor of site productivity (Schönau, 1987), possibly being related to both nutrient and moisture supply. Nitrogen critical loads have been investigated by Emmett and Reynolds (1996). The long term effects of N remain unclear though there is potentially enhanced leaching and aluminium mobilisation. Taylor and Worral (1991) investigated the effect of site factors on the response of Sitka spruce to fertilizer at planting. Soil type influenced the response to P and K application and $P$ to lithology.

Soil morphology has also been used in productivity estimation on the assumption that it reflects the dynamic processes involved in tree growth (Page, 1967, 1970; Tyler et al., 1996; Bateman and Lovett, 1998). The use of major soil groups may not give such precise results as identifying and sampling individual horizons. Soil description and classification often concentrate on agricultural soil properties, though a system was specifically developed for upland forest soils in Britain (Toleman and Pyatt, 1974; Pyatt, 1977). The qualitative form of much soil information has also presented problems in the development of quantitative relationships and the use of dummy variables may only give the impression of greater accuracy.

Variation in surface geology can be included with soil factors. Stendahl et al. (2002) investigated the improvement in yield prediction, at a local scale, from geological and geochemical data. Mineralogy explained $37 \%-61 \%$ of variation in site index with stronger relationships in mineral rich than in mineral poor areas.

### 2.5.8 Multi-factorial approaches

More recent work is taking a so called multi-factorial approach, although in Germany a more holistic approach was adopted as early as the late 1940s in Baden-Württemburg (Barnes et al., 1998). This was a far sighted integration of different disciplines and is used in long term planning and practical management. The system operates at a range of scales; major landscapes are divided into growth areas and minor landscapes into growth districts. This limits more sweeping generalisations. At a more local level ecosystem types are divided into site units that can be mapped at a scale of $1: 10,000$. Physiography, microclimate, soil factors, overstorey and ground cover are all used to describe the site. Individual site units may have similar characteristics but need not necessarily be placed in the same class. This approach was modified and developed for use in Michigan (Albert et al., 1986; Albert, 1995).

Work in Canada has developed along similar lines and progress was reviewed in a special edition of Forestry Chronicle in 1992. Each province has developed its own system of land classification which also has the potential to be used to predict site productivity. The different terminology adopted in these approaches can be confusing but there is a common focus on geographic area or site rather than the stand, "the stage where each unique complex of climate-biota-soil-landform carries its dynamic and ever changing performance directed and invigorated by solar energy" (Rowe, 1992). This reflects the shift towards multiple use forestry rather than concentrating on productivity alone. A great deal of work has been put into the development of these systems (Sims, 1992) and in British Columbia alone over 250 person years have been invested in the ecological description of the province (MacKinnon et al., 1992). Initially vegetation was the key following the work of Cajander (1926) then, in Ontario, Hills (1953) introduced the concept of total site, stressing the role of physiography and integrating climate, vegetation, physiography and soil on landform. This early work in terrain analysis was seen as quite radical at the time (Sims and Uhlig, 1992).

These systems are not attempts to provide accurate predictions of site quality in themselves but can provide the framework for more detailed investigations. Early work into linking site units with productivity has not always been successful (Klinka and Carter, 1990; Page, 1970), but work has continued to improve their predictive ability and to incorporate findings into practical tools for foresters (Ker and Bowling 1991;

Bowling and Zelanzky, 1992). In British Columbia the system provides the basic framework in which to carry out site quality studies (Wang et al., 1994; Klinka and Chen, 2003). Similar work in Britain has resulted in the development of the Ecological Site Classification (ESC, Pyatt et al., 1997, 2001). In ESC, sites can be described in terms of three basic environmental variables: climate, soil moisture regime and soil nutrient regime. Semi-quantitative relationships with productivity have been used to define suitability classes for a range of commercial tree species and site types have also been linked to native woodland types as described in the National Vegetation Classification (Rodwell, 1991; Rodwell and Patterson, 1994).

### 2.5.9 Site factors and productivity

A large amount of work has been (Carmean, 1975; Hägglund, 1981) and continues to be done (e.g. Curt et al., 2001; Dunbar et al., 2002; Chen et al., 2002; Szwaluk and Strong, 2003; Skovsgaard and Vanclay, 2008) to link site factors to the productivity of a wide range of tree species. Many of these studies are empirical in nature but more complex process models are also being developed (Coops et al., 1998; Waring, 2000). There has been a great deal of progress and the advent of modern analysis techniques and computers has aided this (Verbyla and Fisher, 1989). The number and kind of variables used varies, in part dependent on the objectives of the investigation, but in general most investigations use similar measures relating to those factors affecting growth discussed earlier. Many published studies report the development of regression equations similar to equation (2.58), linking site factors to site index.
$S I=a X+b Y+c Z+\ldots$
where $S I$ is site index, $X, Y$ and $Z$ environmental variables and $a, b$ and $c$ site specific parameters. Work by Kahn has attempted to link site variables directly to the parameters of growth models (Pretzsch and Kahn, 1995; Pretzsch, 2002; Pretzsch et al., 2002). Results have been varied. Frequently large amounts of variation can be explained by just a few factors, but there remains the problem of the remaining $20 \%$ or more of variation that cannot be explained. Validation of the models can also present some problems. In early work, generalised site index equations were often used to provide the measure of productivity (Carmean, 1975), and much of the work done in Britain has relied on existing databases (Bateman and Lovett, 1998). A better approach is to
develop specific indices for the sample sites (e.g. Wang et al., 1994). Great care is also needed in site selection (Hamel et al., 2004) and there is a wide variation in the size and number of plots used and sampling technique. One major problem is that the relationships are generally very local and cannot easily be transferred to other regions. The number of possible variables is also large, over sixty being quoted in recent studies (Wang and Klinka, 1996; Tyler et al., 1996; Worrel and Malcolm, 1990a, b; Corona et al., 1998; Marques, 1991; Dunbar et al., 2002). Several studies have indicated that general synoptic measures such as simple topographic variables, higher level soil classes and natural sub-region categories may be sufficient for all the explainable variation in site index (Bateman and Lovett, 1998; Hasenauer, 1997; Wang et al., 2004).

Referring to the problem of the diverse use of site variables, the change in correlations across regions and the fact that causative elements of growth (light, heat, moisture, nutrients and aeration) are rarely the ones measured, Wang and Klinka (1996) looked for a simpler approach to productivity prediction. Frequently just a few variables account for a large proportion in the variation in growth and they recognised that the integration of a few synoptic variables was a potential option. They examined the effects of synoptic measures of ecological site quality on white spruce site index and developed a quantitative link between ecological site classification and forest productivity. Their methods are typical of many more studies, though details of plot numbers and size vary. They sampled 102 stands covering 6 variants of one climatic zone in British Columbia, trying to cover as wide a range of site types as possible. Stands were naturally established and even aged and had to show no evidence of damage. Plot size was 0.04 hectares. A range of site variables were measured but these were reduced to soil moisture regime, soil nutrient regime and soil aeration regime for the analysis. Climatic factors were also built into the models. Site index was estimated from stem analysis of the three largest trees per plot.

Although the models did indicate the possibility of using synoptic variables, Wang and Klinka (1996) urged caution in interpreting results. The relative role of each variable remains uncertain and seems to vary from site to site. Sampling design was a source of complication with under-representation of certain site types. Also the quality of the available climatic data may have influenced the results. In other work Wang et al.
(1994) could not discount the influence of climate even in one relatively restricted climatic zone.

In Britain, investigations into site variables and productivity were carried out by Page (1967) and Mayhead (1968). Mayhead concentrated on vegetation and concluded that results could be improved if other factors were also taken into account. Page investigated climatic, soil and physiographic variables and their effect on three coniferous species. Several regression models were produced but all had restricted geographic use and the effect of different variables was not consistent between species or sites. Page was partly restricted in the quality of data available to him, particularly climatic information. In Page's work elevation consistently appeared as a major explanatory variable for top height variation and Mayhead (1973) tried to quantify the effect of elevation on productivity of Sitka spruce in upland Britain.

More detailed work on Sitka spruce in upland Britain was carried out by Worrel and Malcolm (1991a, b). They used 187 temporary sample plots along transects from a total of 37 upland sites in Scotland and Northern England. Plots were 0.04 ha and general yield class was estimated from top height and standard yield tables. One of their main objectives was to identify easily measured environmental factors to predict productivity and define upper planting limits. A correlation between general yield class (GYC) and elevation at individual sites was found but there was also considerable site to site variation. For any given elevation, GYC was higher inland and in the south than by the coast and in the north. The spatial pattern fitted in with known patterns of windiness and temperature but relationships were complex.

Investigations into site factors indicated that exposure had a significant effect on productivity. Correlation with soil moisture was poor but no lowland sites were investigated and there are indications that moisture stress may be a factor in these situations (Jarvis and Mullins, 1987). The climatic variables were able to explain 78\% of yield class but the edaphic contribution was small. This may have been due to a restricted number of sites, correlation with elevation and modern site amelioration techniques. Soil depth had only slight significance. The elevation and location effects are related to climate and shelter is significant. Aspect is complicated by the prevailing wind pattern and so south west aspects did not fare as well as might be expected. The limitations of this type of exercise are acknowledged and it is pointed out that
predictions might not be much better than those afforded by expert knowledge. Also the geographic limitations of the model to the area of development are acknowledged. Worrel (1987) summarized and presented the findings in a format intended to aid land evaluation and investment decision making.

The work of Worrel and Malcolm was extended to lowland sites by MacMillan (1991). The aims were to quantify variation in GYC on better land in Scotland, to develop a predictive model of productivity and to draw inferences about site factors. He used a combination of principal components analysis and regression and found that $36.8 \%$ of total variation in GYC was explained by 10 site and crop variables. Sites from south and east Scotland were chosen, concentrating on better quality land. Plots were 0.03 ha and top height determined from the three largest diameter trees per plot in order to determine yield class. Tree age was taken from crop records. Soil pits were dug to describe major soil groups and sub-groups and classified using the system of the Soil Survey of Scotland. Topex and elevation were taken from maps and climatic data were replaced by yield class zone. 128 data sets were available for analysis. It was found that no one factor had an overriding effect and elevation was weaker than in the upland study. Exposure as measured by topex was important as was soil moisture which perhaps explains why the upland model overestimates GYC in the lowlands. The crop age effect was very pronounced as it was in the upland work and in the work of Tyler et al. (1996) for other conifer species. Possible reasons given were improved silvicultural practice from the 1950s onwards, higher agricultural inputs, genetic improvement and the effects of environmental pollution. The latest research highlights the effects of raised atmospheric $\mathrm{CO}_{2}$ and N levels and increased warming due to climate change as being likely causes of increased growth in recent decades (Pretzsch, 1996; Spiecker et al., 1996; Cannell et al., 1998; Proe et al., 1996). MacMillan (1991) acknowledges that problems in the use of GYC, possible inaccurate measurement of variables, inaccurate crop age, and inappropriate choice of variables could all be factors to be considered. Even so the model still performs better than Worrel's (1987) or the guidelines given by Busby (1974) and could be used for general guidance.

Tyler et al. (1996) investigated the relationships between site conditions and species other than Sitka spruce in Britain. They relied heavily on the Forestry Commission subcompartment database to do an initial sift of sites. They concentrated on pure sites
which were not naturally regenerated and were greater than 1 ha in size. The age range was 20 to 60 years and the species were Douglas fir (Pseudotsuga menziesii (Mirb.) Franco), Japanese larch (Larix kaempferi (Lamb.) Carrière) and Scots pine (Pinus sylvestris L.). A slightly different set of variables was used than had been the case in previous British work and it was found that mean spring temperature was an important factor for all species. Exposure as measured by topex was correlated with Douglas fir and Japanese larch productivity. A field model was produced in which climatic variables were replaced simply by northing.

One aspect of Worrel and Malcolm's (1991) work was that they were able to use extrapolated climatic data rather than that from the nearest meteorological stations to the site being investigated. Such spatial information is increasingly being used in growth and yield studies along with digital elevation models and geographic information systems.

A framework for regional scale prediction of GYC of Sitka spruce in Scotland was developed by Allison et al. (1994) and linked to a GIS at 1 km resolution. Analysis of data from 487 sites accounted for $59 \%$ of variation in GYC. Data came from a variety of sources including generalised climate surfaces and the 1:250,000 soil map of Scotland. Regression techniques were used. Several simplifications had to be made, for example mineral soils were all eventually lumped together in one class. There was no variable for exposure unlike in other studies in Britain where this has been found to be a key element. Main predictor variables were winter temperature, March temperature, April/June rain, July/September rain, mean rain/temperature April/June and mean rain/temperature July/August. The final map shows a distinct elevation effect and higher GYC in the west of the country The authors thought the level of exposure ought to be incorporated into the model along with more relevant soil information. Despite some obvious limitations, the overall framework of the approach seems to be quite flexible.

Similar work was carried out for the whole of Wales by Bateman and Lovett (1998). They took data from the Forestry Commission sub-compartment data base and LandIS National soil map. Principal components analysis and regression were then used to predict yield class. The GIS was used to extrapolate results and generate a map for the whole of Wales and the maps compare favourably with those previously reported. There is a wide-ranging discussion on the problems of the methods used, especially regarding
the interpolation of the data for elevation, climate and soils. The reliability of the subcompartment data base is not considered however. The model was tested and found to be accurate to within 2 yield classes. As in the work of Allison et al. (1994), the resultant map indicates a trend with elevation. The resolution is not very great but may be useful for broad planning purposes and again the framework has potential to be developed.

## 3 MATERIALS AND METHODS

The main purpose of data collection was to provide information on the range and magnitude of parameter values for the Wenk model (Wenk, 1994) when applied to Sitka spruce across a range of site types in Wales. It was therefore necessary to use a sampling method that could provide sufficient growth data to allow reliable estimates of both individual tree and stand parameters. The objectives were to have as wide a range of sample sites as possible, and within those sites a sufficient number of trees, to establish the range of parameter values which reflect both within and between stand variation. A rapid method (Geißler and Wenk, 1988; section 3.5.1) was used which allowed volume increment data to be gathered without recourse to either time consuming repeated measurements from sample plots or stem analysis. Using this method ten year increment data for a large number of trees covering a wide range of site types can be gathered relatively quickly. Several stem analyses were carried out for each site to check and complement the method. In addition basic inventory information was also collected. Environmental information was extracted from existing databases.

### 3.1 Site Selection

### 3.1.1 Selection criteria

The following criteria were used to guide site selection:

1 As wide a range of yield classes and site types as possible.
2 Pure stands of Sitka spruce.
3 Stands of at least 40 years of age.
4 Unthinned or not thinned in the previous ten years.
5 Uniformity of site.
6 Minimum area of 1.5ha.
7 Ease of access to the site.

### 3.1.2 Site location

An initial search of Forestry Commission Wales' sub-compartment data base (SCDB) was carried out and a list of potential sites drawn up. Approaches were also made to private woodland managers who provided details of further possible locations. Field visits were then carried out to check the suitability of the sites and a final selection made.

A total of seventeen sites at six locations were chosen, representing a wide range of yield classes and site conditions. Of the seventeen sites, six were located in Gwydyr Forest (GWY3, 4, 5, 6, 7 and 8) and five in Clocaenog Forest (CLG8, 9, 10,11, 12). Three sites were established on the Llŷn Peninsula (GFS1 and UPM1 and 2) and one on Anglesey (PEN1). The remaining two sites were located in mid Wales on the margin of the Brecon Beacons at Bryn Arau Duon (BAD1 and 2). A general location map is shown in Fig. 3.1. Table 3.1 gives an overview of the main stand and site characteristics for the sites.


Figure 3.1 Location of temporary sample plots in north and mid Wales

Table 3.1 General characteristics of the temporary sample plots.

| Location | Gwydyr |  |  |  |  |  | Glasfryn | Bryn Arau Duon |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Plot name | GWY 3 | GWY 4 | GWY 5 | GWY 6 | GWY 7 | GWY 8 | GFS 1 | BAD 1 | BAD 2 |
| Grid reference | SH770574 | SH763552 | SH766557 | SH764558 | SH773513 | SH773515 | SH409432 | SN750488 | SN743480 |
| Longitude <br> Latitude | $\begin{aligned} & 3^{\circ} 50^{\prime} \mathrm{W} \\ & 53^{\circ} 06^{\prime} \mathrm{N} \end{aligned}$ | $\begin{gathered} 3^{\circ} 51^{\prime} \mathrm{W} \\ 53^{\circ} 05^{\prime} \mathrm{N} \\ \hline \end{gathered}$ | $\begin{aligned} & 3^{\circ} 51^{\prime} \mathrm{W} \\ & 53^{\circ} 05^{\prime} \mathrm{N} \end{aligned}$ | $\begin{gathered} 3^{\circ} 51^{\prime} \mathrm{W} \\ 53^{\circ} 05^{\prime} \mathrm{N} \\ \hline \end{gathered}$ | $\begin{gathered} 3^{\circ} 50^{\prime} \mathrm{W} \\ 53^{\circ} 03^{\prime} \mathrm{N} \end{gathered}$ | $\begin{aligned} & 3^{\circ} 50^{\prime} \mathrm{W} \\ & 53^{\circ} 03^{\prime} \mathrm{N} \end{aligned}$ | $\begin{aligned} & 4^{\circ} 22^{\prime} \mathrm{W} \\ & 52^{\circ} 58^{\prime} \mathrm{N} \\ & \hline \end{aligned}$ | $\begin{gathered} 3^{\circ} 50^{\prime} \mathrm{W} \\ 52^{\circ} 07^{\prime} \mathrm{N} \\ \hline \end{gathered}$ | $\begin{gathered} 3^{\circ} 50^{\prime} \mathrm{W} \\ 52^{\circ} 07^{\prime} \mathrm{N} \\ \hline \end{gathered}$ |
| Altitude [m.a.s.l.] | 105 | 305 | 265 | 295 | 360 | 360 | 150 | 350 | 410 |
| Accumalated temperature (day degrees above $5^{\circ} \mathrm{C}$ ) | 1619 | 1265 | 1336 | 1283 | 1170 | 1170 | 1565 | 1444 | 1139 |
| Moisture deficit (mm) | 136 | 84 | 95 | 87 | 70 | 70 | 119 | 104 | 632 |
| DAMS (windiness) | 8 | 16 | 12 | 16 | 18 | 18 | 15 | 12 | 19 |
| Soil type | (Gleyed) Brown earth | Deep peat Peaty Gley | Peaty gley | Deep peat | Peaty gley | Deep peat | SWG <br> Peaty gley | Upland brown earth | Unflushed Deep peat |
| Soil Moisture Regime | fresh/moist | very wet | wet | very wet | wet | very wet | very moist | fresh | very wet |
| Soil Nutrient Regime | medium | very poor | poor | very poor | poor | very poor | medium | poor | very poor |
| Total Plot size $\left[\mathrm{m}^{2}\right]$ | 6000 | 1500 | 7500 | 7500 | 7500 | 7500 | 7500 | 3000 | 1500 |
| Stand age at survey [a] | 37 | 40 | 40 | 40 | 40 | 40 | 41 | 39 | 40 |
| Number of trees $\mathrm{ha}^{-1}$ | 1242 | 2650 | 1673 | 2213 | 2193 | 3133 | 1405 | 1460 | 3520 |
| Top height [m] | 24.8 | 17.7 | 26.8 | 15.0 | 22.0 | 10.9 | 23.1 |  |  |
| $\mathrm{H}_{100}$ [m] | 25.3 | 18.1 | 26.8 | 15.4 | 22.0 | 10.9 | 23.5 | 24.7 | 13.6 |
| $\mathrm{D}_{\mathrm{g}}[\mathrm{cm}]$ | 20.13 | 15.6 | 19.8 | 16.0 | 20.5 | 10.6 | 20.3 | 25.6 | 14.8 |
| BA [m²/ha] | 35.42 | 50.72 | 51.49 |  | 72.25 | 27.46 | 45.51 | - | - |
| Yield class (SCDB) | 22 (22) | 12 (8-20) | 23 (8-20) | 10 (8-20) | 17 (14-20) | 6 (2) | 18 (na) | 20 (na) | 6 (na) |
| Yield class (ESC) | 18 | 12 | 18 | 13 | 14 | 12 | 20 | 18 | 13 |

An explanation of the terms for the environmental variables can be found in Pyatt et al. (2001), Kennedy (2002) and Quine and White (1993).
Top height is the average height of the 100 largest diameter trees per hectare; $\mathrm{H}_{100}$ is estimated from site specific height:diameter curves; $\mathrm{D}_{\mathrm{g}}$ is the diameter of the tree of mean basal area; BA is stand basal area.
Yield class is estimated from Forestry Commission yield tables (Edwards and Christie, 1981); (SCDB) is the yield class recorded in the sub-compartment data base.
Yield class (ESC) is estimated from the ESC decision support system, ESC to go (Ray, 2001).

Table 3.1 cont. General characteristics of the temporary sample plots

| Location | Clocaenog |  |  |  |  | Pentraeth | Llŷn |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Plot name | CLG8 | CLG9 | CLG10 | CLG11 | CLG12 | PEN1 | UPM1 | UPM2 |
| Grid reference | SH957560 | SJ045507 | SJ033525 | SH962584 | SH961587 | SH544787 | SH325368 | SH310397 |
| Longitude <br> Latitude | $\begin{aligned} & 3^{\circ} 34^{\prime} \mathrm{W} \\ & 53^{\circ} 05^{\prime} \mathrm{N} \end{aligned}$ | $\begin{aligned} & 3^{\circ} 26^{\prime} \mathrm{W} \\ & 53^{\circ} 03^{\prime} \mathrm{N} \end{aligned}$ | $\begin{aligned} & 3^{\circ} 27^{\prime} \mathrm{W} \\ & 53^{\circ} 04^{\prime} \mathrm{N} \end{aligned}$ | $\begin{gathered} 3^{\circ} 33^{\prime} \mathrm{W} \\ 53^{\circ} 07^{\prime} \mathrm{N} \\ \hline \end{gathered}$ | $\begin{aligned} & 3^{\circ} 33^{\prime} \mathrm{W} \\ & 53^{\circ} 07^{\prime} \mathrm{N} \end{aligned}$ | $\begin{aligned} & 4^{\circ} 11^{\prime} \mathrm{W} \\ & 53^{\circ} 17 \mathrm{~N} \end{aligned}$ | $\begin{aligned} & 4^{\circ} 29^{\prime} \mathrm{W} \\ & 52^{\circ} 54^{\prime} \mathrm{N} \end{aligned}$ | $\begin{aligned} & 4^{\circ} 31^{\prime} \mathrm{W} \\ & 52^{\circ} 56^{\prime} \mathrm{N} \end{aligned}$ |
| Altitude [m.a.s.I.] | 420 | 325 | 345 | 445 | 435 | 115 | 25 | 155 |
| Accumulated temperature (day degrees above $5^{\circ} \mathrm{C}$ ) | 1058 | 1229 | 1192 | 1012 | 1030 | 1585 | 1789 | 1552 |
| Moisture deficit (mm) | 58 | 85 | 79 | 52 | 54 | 127 | 149 | 115 |
| DAMS (windiness) | 20 | 16 | 15 | 20 | 20 | 13 | 13 | 12 |
| Soil type | Peaty gley Deep peat | Brown earth | SWG <br> Brown earth | Peaty gley | Deep peat | $\begin{gathered} \text { SWG } \\ \text { Peaty gley } \\ \hline \end{gathered}$ | Deep peat | Brown earth |
| Soil Moisture Regime | very wet | fresh | moist | very moist | Very wet | very moist | very wet | fresh |
| Soil Nutrient Regime | very poor | medium | medium | poor | very poor | medium | medium | poor |
| Total Plot size [ $\mathrm{m}^{2}$ ] | 6000 | 7500 | 1500 | 7500 | 7500 | 7500 | 7500 | 7500 |
| Stand age at survey [a] | 41 | 38 | 35 | 45 | 45 | 48 | 43 | 49 |
| Number of trees $\mathrm{ha}^{-1}$ | 2147 | 1027 | 1567 | 1227 | 3027 | 1080 | 1860 | 1527 |
| Top height [m] | 18.8 | 24.8 | 31.3 | 24.3 | 13.2 | 30.8 | 22.2 | 22.3 |
| $\mathrm{H}_{100}[\mathrm{~m}]$ | 19.3 | 25 | 31.5 | 24.7 | 14.1 | 30.8 | 22.5 | 22.7 |
| $\mathrm{D}_{\mathrm{g}}[\mathrm{cm}]$ | 17.8 | 27.6 | 26.0 | 27.2 | 11.7 | 29.8 | 21.5 | 23.5 |
| BA [ $\left.\mathrm{m}^{2} / \mathrm{ha}\right]$ | 53.38 | 61.45 | 82.98 | 71.45 | 32.69 | 75.32 | 67.42 | 65.27 |
| Yield class (SCDB) | 14 (12) | 21 (18) | 30 (24) | 17 (16-20) | 6 (0) | 24 (14) | 16 (na) | 14 (na) |
| Yield class (ESC) | 11 | 17 | 17 | 11 | 11 | 19 | 16 | 20 |

### 3.2 Site description

### 3.2.1 Gwydyr

Gwydyr is a diverse forest and a wide range of site types was sampled with reported yield class from below eight to twenty two. GWY4, 5 and 6 are located in the same large compartment but have contrasting ground conditions and yield class. GWY 7 and GWY8 are within 200 m distance from each other at the same elevation but have very different yield class.

### 3.2.1.1 GWY3

GWY3 is in a sheltered position with northerly aspect. The site has a uniform gentle slope, with occasional rocky outcrops, but includes a short steeper slope above wet ground on the northern side. The sub-compartment database lists the soil type as iron pan soils but brown earths with occasional gleyed conditions are also present. The stand has been thinned, it is believed over ten years previously, but no history is available. There is a single rack running through the plot and variable density and size of trees throughout the site. Suggestions that some parts of the stand may have consisted of natural regeneration could not be proved and no age differences were found in the sample trees. Because of site limitations, only 12 plots could be established and these plots could not be laid out in a regular grid. Only one tree was sampled for stem analysis.

### 3.2.1.2 GWY4

GWY4 is in an exposed position on the southern margin of the forest. Trees on the forest margin exhibit stunted growth because of this, though more sheltered conditions result in improved growth less than 100 m into the stand. This part of Gwydyr was planted on broken moorland consisting of narrow, rocky ridges with thin mineral soils separated by equally narrow strips of flushed and unflushed deep peat. It was not possible to lay out the plots on a regular grid and every effort was made to ensure uniformity of site type, particularly by avoiding the ridges which were dominated by lodgepole pine (Pinus contorta, Douglas). There is some variation in the quality of the stand, Sitka spruce performing better on sites where gentle slopes provide better drainage. Parts of the site showed signs of check and attempts to rectify this in the past were evidenced by the presence of discarded fertiliser bags. The stand was unthinned
and dense at the time of site establishment and disc sampling but was thinned before the plots could be assessed. Alternative plots were established to gather inventory data.

### 3.2.1.3 GWY5 and GWY6

GWY5 has a similar topography to GWY4 but has an overall steeper gradient and has better and more uniform tree growth. Plots were laid out in an irregular pattern keeping as far as possible to flush lines. Soil type is a peaty gley.

GWY6 was located close to GWY5 but in contrast to this site is dominated by unflushed deep peat. The central part of the plot is very wet with standing surface water in places, but other parts are slightly raised and provide improved rooting conditions. Nine of the plots were established on a grid pattern, the remainder in short lines attached to the grid.

As with GWY4 these sites were thinned after disc samples were taken and modified plots were used to gather inventory data.

### 3.2.1.4 GWY7 and GWY8

These two sites were located close to each other on the edge of a broad plateau where they receive some shelter from the surrounding crop. GWY7 has gentle slopes with peaty gley soils. The site has been drained and growth is uniform throughout the stand. By contrast GWY8 is on wet, unflushed peat with surface water in places and growth is very uneven. A grid layout was possible at both sites. Only twelve plots could be established at GWY8 because of space limitations and so two trees were taken from three of the plots.

Clocaenog Forest covers part of a relatively high dissected plateau most of which is above 300 m rising to 500 m . The underlying solid geology is Silurian made up of slates, shales and grits and provides similar soil parent materials to those of the Ordovician which dominates Gwydyr Forest. Soils are generally fine textured though often quite stony. Upland brown earth and iron pan soils predominate where site drainage is sufficient but there are rapid and subtle changes in drainage status within the same general soil type. Where the site is less well drained surface water and peaty gleys occur. The climate is relatively harsh with cool temperatures and high rainfall and windspeed.

### 3.2.2.1 CLG8

CLG8 is located on a broad interfluve, with negligible slope, dominated by weakly flushed peat and peaty gleys. The site has been drained but the stand is of somewhat uneven growth. The plots were laid out in two rows of six and one row of three.

### 3.2.2.2 $C L G 9$

CLG9 is on a more or less uniform gentle slope with westerly aspect. The dominant soil type is brown earth with occasional rocky outcrops. The stand has been thinned at least once but not within the last ten years and there are several small gaps due to windblow. Plots were laid out in a grid pattern, and located wholly between racks which were approximately seven metres apart.

### 3.2.2.3 CLG10

This site was established on a gently sloping lower slope adjacent to agricultural land. Soils vary from brown earth to surface water gley. Trees are fast growing and the stand is self thinning due to mortality. It was not possible to establish a grid layout but plots were kept as close to each other as possible to ensure uniformity of site type.

### 3.2.2.4 CLG11

CLG11 is on the margin of a high level plateau with gentle to moderate slopes dominated by peaty gley soils. The stand has been line thinned though not within the previous ten years and individual plots were established to take into account the thinning pattern.

### 3.2.2.5

CLG12 is only 400 m distant from CLG11 and at a similar elevation. The site is dominated by deep unflushed peat. The peat has been drained but growth is uneven with several parts continuing to grow poorly. There is better growth where the ground conditions appear to be drier. Plots were laid out in three parallel lines.

### 3.2.3. Bryn Arau Duon

Two plots were established in this private forest on the edge of the Brecon Beacons. The larger part of the forest was planted in the early 1960s and remained unthinned until the recent past due to concern over possible wind damage. Several sites remain unthinned and the plots were selected from these. The forest is situated on a broad rounded plateau with steeper side slopes. The plateau top is marked by poorly drained areas of blanket bog separated by gently sloping areas of peaty gley and iron pan soil. On steeper slopes brown earths with more or less peaty surface horizons occur.

### 3.2.3.1 BADI

BAD1 is situated on a north facing slope at approximately 350 m elevation with north easterly aspect. The site is bordered by a small stream to the north and steeper slopes to the south. Soils are freely draining brown earths with thin peaty surface horizons. The slope of the ground varies but is generally less than $10 \%$. The plots were laid out to take into account slight variations in site conditions.

### 3.2.3.2 BAD2

BAD2 is on the plateau summit at approximately 410 m . The site is part of an extensive blanket bog broken by broad mounds of drier ground. Deep peat is exposed in drainage ditches and the site remains wet. Elsewhere the peat is unplanted or the trees have failed. Ten of the plots were laid out in a grid pattern the remaining five were offset from this grid but located in similar situations.

### 3.2.4

### 3.2.4.1 GFSI

The site is on a broad bench or plateau area with poorly drained soils, mainly typical surface water gleys occasionally with a thin peaty surface horizon. The stand was planted in the early 1960s and although there has been some minor thinning this has not been systematic and there has been none within the last 10 years. A combination of wind climate and poorly drained soils has contributed to a serious problem with windthrow throughout the estate and the margins of the site are affected by this. The plots were established in a regular grid pattern.

### 3.2.4.2 UPM1 and UPM2

UPM1 is a low lying site on the margin of agricultural land. The site is level with some minor undulations. Soils are peaty gleys and though drains have been installed some parts of the stand are wet. UPM2 was on a steep north facing slope with shallow brown earth soils, with occasional narrow flushes and rocky outcrops. Both sites are unthinned and plot layout was in a grid pattern.

### 3.2.4.3 PENI

This site is on an irregular east facing slope with narrow flush lines opening into broader more level sections. Surface water gleys dominated the flush lines. A grid layout was not possible and plots were kept, as far as possible, in the wetter zones.

### 3.3 Site Establishment

### 3.3.1 Protocol

The protocol for the sample tree method requires a minimum of ten trees to be sampled from each site (Geißler and Wenk, 1988). This was increased to fifteen trees for this study to ensure adequate coverage across the diameter range. An added benefit of doing this is that unsuitable data could be discarded without seriously compromising the analysis. Three of the trees were also sampled for stem analysis in order to provide additional data on tree growth and provide a check for the sample tree method. In principle the sample trees could have been taken from anywhere within the stand but it was decided to follow a fixed sampling pattern wherever possible to ensure better coverage and decrease variance. The trees were also located within temporary sample
plots which provided basic information about the stand. Wherever possible the temporary plots were laid out in a grid pattern, the distance between plots being determined by their size. Plot centres were approximately 30 m apart for 0.05 ha plots and 12 m to 15 m apart for 0.01 ha plots. Where site conditions dictated, the distance between plots was varied and they were located to maintain uniformity of site type. The sites were established in two main field programmes. In the first phase five sites were examined in order to test the basic assumptions of the methodology and practical aspects of the sampling programme. Once the methodology had been tested a further 12 sites were measured and sampled.

### 3.3.2 Establishment of temporary plots

Two approaches were used to establish the temporary plots. In the first the sample tree was chosen and used as the plot centre. An approximate position for the next plot centre was chosen so that it conformed to the grid pattern and the nearest suitable tree for sampling chosen as the centre. This was done partly to minimise edge effects during spatial analysis. Later plots were established without regard to the position of sample trees the latter being chosen after an inventory of the plots had been made. This made initial plot set up much more rapid.

In the first approach the stand was first examined and sample dbh measurements taken. Having established a maximum and minimum value this range was then partitioned into fifteen size classes of equal width. Class width was not important the emphasis being on sampling evenly across the diameter range. An arbitrary starting point within the stand was chosen and the dbh of several trees measured and recorded on a sketch map of the site. A second set of measurements were taken approximately 30 m (for 0.05 ha plots) away and again until fifteen plot centres were approximately positioned on a four by four square grid leaving one of the corners empty. One of the measured trees was then chosen as the centre of each plot ensuring that a complete sample of the dbh range was obtained. The chosen trees were then examined more carefully and any that looked to have obvious crown damage were rejected. By keeping centres 30 m apart there was some scope to move the plot centre to avoid overlap of adjacent plots.

In the second phase of sampling temporary plots were established prior to choosing a sample tree and there was no initial assessment of the dbh range of the stand. As far as possible a grid pattern was retained. If a grid pattern was not possible plots were established so as to ensure similar site conditions and fixed distances maintained between plot centres. Diameter classes were designated after an inventory of the plots had been taken. Sample trees could come from anywhere within a plot and were chosen in a more or less arbitrary fashion ensuring that every diameter class was represented. The chosen trees were then examined in the field and changes made if these were found to be unsuitable.

Within each plot diameter at breast height of all trees was measured. The height of the largest diameter tree in each plot was also taken and a further thirty to forty heights selected from all plots and from across the diameter range.

### 3.4 Sampling procedure

3.4.1 Rapid method theory

The measurement and sampling of trees is based on the fact that volume can be determined from the height $(h)$ and mean cross sectional area $\left(b a_{\mathrm{q}}\right)$ of the tree. The calculation is simply that for the volume of a cylinder because the form factor at this point is equal to one.

$$
\begin{equation*}
v=h \cdot b a_{q} \tag{3.1}
\end{equation*}
$$

where
$v \quad$ volume $\left(\mathrm{m}^{3}\right)$
$h \quad$ tree height (m) measured from felling cut
$b a_{q} \quad$ mean cross sectional area $\left(\mathrm{m}^{2}\right)$

To determine mean cross sectional area mean diameter is calculated following Radonjic (1954):
$d_{q}=\sqrt{\frac{k}{3} \cdot\left(d_{1 / 8}^{2}+d_{4 / 8}^{2}+d_{7 / 8}^{2}\right)}$
where
$d_{q} \quad$ mean diameter (cm)
$d_{\mathrm{n} / 8} \quad$ diameters at $\frac{\mathrm{n}}{8}$ of the height of the tree (cm)
$k \quad$ a tree specific constant

The constant, $k$, can be determined through stem analysis and typical values are listed in table 3.2. A value of 1.0395, established following stem analysis of trees sampled during the Tyfiant Coed Project, was used in this study.

Table $3.2 \quad$ Values of the correction factors $k$ for the main tree species.

| Species | $k$ |
| :--- | :---: |
| Pine, spruce, oak, ash | 1.030 |
| Larch, birch, alder | 1.045 |
| Beech | 1.025 |
| Sitka spruce | 1.040 |

Current volume is relatively easy to estimate once mean cross sectional area has been determined. In order to calculate relative volume increment over a 10 year period height and mean cross sectional area from 10 years ago ( $h_{-10}$ and $b a_{q-10}$ ) are also required. Height from ten years ago is estimated by counting back branch whorls and the position of mean cross sectional area can be determined from a ratio of current total height and height to $d_{q}$ (equation 3.3) on the assumption that there has been no change in form factor during the previous 10 year period. A sample disc is collected and $d_{q-10}$ can be measured from this. The variables required are illustrated in Fig. 3.2.
$h_{0-10}=\frac{h_{0}}{h} \cdot h_{-10}$


Figure 3.2 The variables to be measured for the determination of the volume increment of the last ten years. (Geißler and Wenk, 1988)

| $h$ | current tree height measured from cutting point <br> tree height 10 years ago |
| :--- | :--- |
| $h_{-10}$ | height to current mean cross sectional area |
| $h_{0}$ | height of mean cross sectional area 10 years ago |
| $h_{0-10}$ | diameter of mean cross sectional area <br> $\mathrm{d}_{\mathrm{q}}$ |
| $\mathrm{d}_{\mathrm{q}-10}$ | diameter of mean cross sectional area 10 years ago |
| (all heights in metres; all diameters in centimetres) |  |

### 3.4.2 Height measurement and whorl count

Sample trees were felled and delimbed avoiding excessive bark damage. The top ten whorls were left intact to facilitate identification of the height of ten years ago. Total tree height was measured to the nearest 0.1 m from felling cut which was assumed to be at 0.3 m above ground level. On small trees with short internodes height was measured to the nearest 0.05 m . Breast height was taken as 1 m above felling cut. Height ten years ago was measured to the tenth whorl below the tip of the tree. Whorls were counted back very carefully and, where there was ambiguity, the position of the tenth whorl was checked by counting growth periods on side branches and/or by cutting the stem above the whorl and counting the rings. There should be 10 internodes on side branches at the
tenth whorl and ten rings above it. Problems counting nodes existed when two apparent nodes occurred close together which may have been the result of lammas growth, a genetic trait or previous damage to leaders. This phenomenon occurred particularly on faster growing trees. Occasionally the growing point seemed to be above the whorl indicated by a distinct narrow groove circling the stem. Loss of, and damage to, current leader (a frequent occurrence with fast growing trees) could result in misidentification of the tenth whorl. In this situation it was generally possible to estimate the length of the leader by examination of the side shoots and previous years' leader extension. On stem analysis trees only, the height to all whorls that could be confidently identified was also measured.

### 3.4.3 Diameter measurement

Diameters were measured to the nearest 1 mm using a research grade diameter tape. For all trees diameter was measured at the three positions described in section 3.4.1 in order to determine mean tree diameter. The position of this diameter was then located and its height above felling cut measured to the nearest 0.1 m . The position of mean tree diameter of ten years ago was then calculated using equation 3.3.

### 3.4.4 Disc cutting and labelling

Following measurement the trees were marked at the required positions for disc sampling with a short vertical stroke using a scribe. Discs of approximately 5 cm thickness were cut with either a chainsaw or handsaw, the upper cut at a point just above the scribe mark. This assisted in later orientation of the disc for labelling purposes. Damage to bark was avoided as far as possible. Those discs cut with a handsaw generally required less preparation later. Two discs were cut from all trees, at breast height and at mean diameter from 10 years ago. Additional discs were taken from stem analysis trees at two metre intervals from breast height i.e. $3 \mathrm{~m}, 5 \mathrm{~m}$ etc. and also a disc from the stump i.e. 0 m . Discs were then carefully labelled with site, tree and position on tree and transported back to the workshop for further preparation.

### 3.5 Disc preparation

### 3.5.1 Planing and labelling

Discs were prepared for analysis as soon as possible after sampling in order to avoid shrinkage and cracking. If there was any delay discs were kept covered and as cool as possible. To produce a surface suitable for marking, scanning and measurement the discs were planed using an electric plane. Care was needed not to break the bark during this process though small sections of missing bark could be avoided during measurement of the discs. If the early wood was particularly soft it tended to rip rather than cut and this could lead to uneven surfaces or make ring identification difficult. Occasionally the boundary between bark and wood would fray which which led to similar problems of ring identification. If the surface of the disc was very uneven after planing (a problem with larger discs) out of focus images resulted. However this did not present serious problems in identifying and marking rings.

After planing discs were marked with a minimum of four radii which were paths along which identification and measurement of rings would take place (Fig. 3.3). If the discs were very eccentric in shape then eight paths were marked with $45^{\circ}$ between paths. The paths were oriented on the disc following the procedure of Siostrzonek (1958). To determine the position of the paths the longest radius was first found using a pair of compasses or dividers and its position marked. Path 1 was then offset from this radius by $221 / 2$ degrees. It could be placed either side of the longest radius and unfavourable ring patterns, e.g. around knots and broken bark could be avoided. The remaining paths were then marked, those at $90^{\circ}$ intervals from path 1 always being designated $2-4$ and those at $45^{\circ} 5-8$.

### 3.5.2 Scanning

The discs were scanned and the images saved for further analysis. Spraying the discs, lightly with water improved the contrast in the image. For most discs a resolution in grey scale of 300 dots per inch was adequate for ring identification and measurement. For some discs with close spaced rings resolution was increased to assist in separation of rings at higher magnification. For the same reason several discs were also scanned in colour but this greatly increased the file size which could impair the working of the analysis software for only marginal improvement in ring detection.


Figure 3.3 Paths marked on tree discs prior to scanning. Paths 5 to 8 were used only if the disc was very eccentric.

### 3.6 Ring count and measurement

The specialist software WinDENDRO (Regent Instruments Inc.) was used to mark and count tree rings and measure their width. For stem analysis discs all rings were marked. For $h_{0-10}$ discs it was necessary only to mark the ring from 10 years ago to give diameter under bark from 10 years ago. Diameter over bark could then be calculated using a bark function. However the final year ring was also marked in order to measure bark thickness and develop a site specific bark function.

In cases where it was difficult to identify rings on the images, the disc itself was examined. A sharp knife was used to create a smooth surface and if the rings were very narrow then a hand lens or microscope was used. Spraying with water improved contrast between early and late wood and therefore ring identification.

### 3.7 Data preparation

### 3.7.1. ASCII files

WinDendro saves ring width data in text files along with more general information for example disc identification. After some modification text files can be imported directly into EXCEL spreadsheets for further analysis. Separate spreadsheets were developed for the rapid method and stem analysis trees. In both, radius or ring width is converted into diameter using the quadratic mean:

$$
\begin{equation*}
d=2 \cdot \sqrt{\frac{r_{1}^{2}+r_{2}^{2}+\ldots r_{n}^{2}}{n}} \tag{3.4}
\end{equation*}
$$

where

| $d$ | diameter of the disc $(\mathrm{cm})$ |
| :--- | :--- |
| $r_{1}, r_{2} \ldots r_{n}$ | radii or annual ring widths (cm) |
| $n$ | number of paths |

### 3.7.2 Volume calculation

### 3.7.2.1 Rapid method trees

Average diameters were used together with height to calculate current volume and volume from ten years ago as described in section 3.5.1. Current volume was calculated from field data using total tree height and cross sectional area at the point of average diameter. Volume from ten years ago was calculated from the $h_{0-10}$ disc. Diameter under bark must first be converted to diameter over bark and was done using either a generalised or site specific bark function. Site specific functions were developed from rapid method and stem analysis trees.

### 3.7.2.2 Stem analysis trees

A semi-automated spreadsheet was developed for stem analysis trees. The spreadsheet calculated cumulative diameters under bark, bark thickness, a bark function, breast height diameter, height, volume and form factor for all ages of the tree.

### 3.8 Estimation of parameters

### 3.8.1 Rapid method trees

Relative volume increment and parameter $c_{1}$ for individual trees were both calculated automatically in a single spreadsheet.

Relative volume increment for the sample trees is:
$p_{V 10}=\frac{V_{2}-V_{1}}{V_{2}}$
where
$p_{\text {v10 }}$ is relative volume increment over a ten year period
$V_{1} \quad$ is volume at the start of the period $\left(\mathrm{m}^{3}\right)$
$V_{2} \quad$ is current volume $\left(\mathrm{m}^{3}\right)$

Parameter $c_{1}$ was calculated by rearranging equation 2.32:
$c_{1}=\frac{-\ln \left(p_{V 10}\right)}{\left.t^{\prime} \cdot\left(1-e^{\left(-c_{2} i^{i} \cdot\left(1-e^{-c 3 s^{i}}\right)\right.}\right)\right)}$
where
$i^{i}$ is transformed age

In equation $3.6 c_{2}$ is kept constant and initially, following recommendations by Wenk et al. (1994) given a value of 1 . Parameter $c_{3}$ is also kept constant with a value of 0.4 . The effect on $c_{1}$ of altering $c_{2}$ and $c_{3}$ values was also investigated. An alternative method of estimating average and individual tree $c_{1}$ values and an optimum $c_{2}$ value is described in section 3.8.2 where procedures for stem analysis trees are presented.

When values of $c_{1}$ are plotted against volume or diameter the data points tend to be quite scattered. The data were smoothed by using a predicted value of volume increment. The latter was estimated from a regression of volume increment plotted against current volume (equation 3.7; Fig. 3.4). Relative volume increment was calculated by substituting the parameters of the regression into equation 3.8.
$i_{V 10}=a+b V_{2}$
$p_{V 10}=\frac{a}{V_{2}}+b$
where

| $i_{\text {VIO }}$ | 10 year volume increment $\left(\mathrm{m}^{3}\right)$ |
| :--- | :--- |
| $\mathrm{V}_{2}$ | volume at end of increment period $\left(\mathrm{m}^{3}\right)$ |
| $a$ | intercept of the regression line |
| $b$ | slope of the regression line |



Figure 3.4 Volume increment function for CLG10. Parameter values: $a=0.0487 ; b=0.5648 ; r^{2}=0.9823 . v$ is volume and $i_{V}$ is volume increment.

New values of $c_{1}$ can now be calculated and typical results are shown in table 3.3 The effect of smoothing the data is illustrated graphically in Fig. 3.5.

Table 3.3 Deriving the volume increment percentage and growth parameter $c_{1}$ of the last ten years (example from GFS1).

| Tree \# | Species | Age | $\mathrm{v}^{2}\left[\mathrm{~m}^{3}\right]$ | $\mathrm{v}-10$ | $\mathrm{i}_{\mathrm{V} 10}$ | $p_{\mathrm{V} 10}$ | $\mathrm{t}^{\prime}$ | Z | $c_{2}$ | $c_{1}$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 8(raw) | SS | 41 | 0.31 | 0.11 | 0.2028 | 0.6461 | 3.1 | 0.7106 | 1.00 | 0.1584 |
| 8(reg) | SS | 41 | 0.31 | $\mathrm{n} / \mathrm{a}$ | 0.1706 | 0.5436 | 3.1 | 0.7106 | 1.00 | 0.2211 |

Raw refers to actual values of volume increment, reg to transformed values; $z$ is equal to ( $1-e^{-c_{3} t^{\prime}}$ ) of equation 2.32 .


Figure 3.5 Relationship between volume and $c_{I}$ of individual trees for CLG10. Solid points are from raw data. The line with open circles was derived from values of volume increment predicted from the function in equation 3.8.

The values of individual tree $c_{1}$ were used to derive estimates of parameter $a$ of equation (2.9), which is repeated overleaf as equation (3.9). This parameter is the minimum value $c_{1}$ can take at any given site and so can be used a measure of site potential (Pommerening and Wenk, 2002).
$c_{1 i, t}=\frac{a}{1-e^{\left(-\frac{x \cdot D B H r a t i o_{i, t}}{b+1}\left(\frac{D B H_{i, t}}{10}\right)^{b+1}\right)}}$
where
$a \quad$ site specific parameter
$D B H_{\text {ratio }} \quad$ measure of competition based on the dbh ratio of the tree and its primary competitor
$x, b \quad$ parameters
Because data to assess competition were not collected this function was modified and $c_{1}$ regressed against volume as well as diameter at breast height:
$c_{1 i, t}=\frac{a}{1-e^{\left(-b Y^{c}\right)}}$
where
$Y$ volume or $\mathrm{dbh} / 10$

Parameter $a$ was compared to other measures of site productivity derived from the inventory data taken from the temporary plots. The regression equation was also used to estimate alternative measures of stand $c_{1}$ including that of the top diameter tree and that of the tree of mean basal area.

### 3.8.2 Stem analysis trees

Parameters for the Wenk model were estimated from equation 2.32 using a programme written in Java. The input file required data for tree number, tree age, height; diameter and volume. Output data were optimum $c_{2}$ and associated constant $c_{1}$ and allometric coefficient $m$. These optimised values were then used as start values in a non linear least squares regression to find $c_{1}, c_{2}$ and $m$. In the input file it was normally sufficient to quote volume to four decimal places and it may be doubted whether the measurements are so precise. However for very small trees there was insufficient differentiation between volume at different ages and volume data were inputted using 6 decimal places.

### 3.8.2.1 Grid search

This initial step for estimating optimum $c_{2}$ values uses iterative methods in which parameter $c_{1}$ is calculated for each year and for all values of $c_{2}$ between 0.5 and 4 in incremental steps of 0.01 or less. The coefficient of variation of $c_{1}$ (following recommendations by Wenk, pers comm) is calculated for each value of $c_{2}$ and optimum $c_{2}$ defined as that which produced the lowest coefficient of variation. Optimum $c_{2}$ and the associated $c_{1}$ value were then used in calculating the allometric coefficient. This routine was very slow, even on the fastest computers, and would fail where optimum $c_{2}$ was less than 0.5 or greater than 4 . The method was therefore modified and a stepwise approach taken to estimating optimum $c_{2}$. The first step was to estimate optimum $c_{2}$ between 0.5 and 100.5 in incremental steps of 10 . By bracketing the resulting optimum value with a narrower range of $c_{2}$ values and running the routine again the increment could be reduced to $1,0.1$ and finally 0.01 . In order to ensure that the true optimum value was reached, rather than a local minimum in coefficient of variation, a graph of the coefficient of variation of $c_{1}$ against $c_{2}$ was plotted for each stage. At the smallest level of increment the pattern of variation could be quite complex and occasionally a choice of two values of optimum $c_{2}$ was possible. These were, however, generally very close together. A typical pattern is for there to be a fall in coefficient of variation of $c_{1}$ with increase in $c_{2}$ value. There would then be some variation around a minimum value before a slight rise to a constant value. Such a pattern is shown in Fig. 3.6. In other cases the value reached a peak then fell to a constant minimum. This minimum was taken as optimum.

Optimum $c_{2}$ and its corresponding $c_{1}$ value were used as starting values in a non-linear regression routine. Initially this routine had 100 iterations but this was found to be insufficient in certain cases. The number of iterations was then increased to 10,000 which did not increase the run time for the routine by any marked extent. It did mean however that the start value for the routine did not have to be so precise and therefore the optimisation part of the routine could be simplified to steps of 1 between the value of 0.5 and 5.5 . In most cases a constant start value for $c_{2}$ of 2.5 would probably be sufficient.


Figure 3.6 Trends in coefficient of variation of $c_{I}$ for different values of $c_{2}$ for tree CLG9-1.

### 3.8.2.2 Simulated annealing

Simulated annealing is a mathematical simulation of the tempering of steel in a blacksmiths forge and can be used to optimise model parameters (Chen and von Gadow, 2002; Pommerening and Stoyan, 2008).

At a predetermined starting temperature an energy level is calculated for the model under investigation. The energy level in this study was the least squared difference between observed and predicted relative volume increment. In a second step model parameters are altered and energy recalculated. If the energy is lower the new model is accepted and preferred to the earlier one. If the energy is higher it may still be chosen depending on a probability function determined by the temperature. As temperature falls the likelihood of higher energy levels being chosen diminishes. This process allows a wide range of parameter combinations to be tested and helps avoid local minima. However, simulated annealing may not always give the global energy minimum
(Michalewicz and Fogel, 2000) and the final outcome can be affected in a number of ways. The following criteria determine the structure of the search space and define neighbourhood, the evaluation function and the initial starting point, all of which can affect the results of the search.

1 Initial temperature.
2 Cooling ratio.
3 Termination condition (before a change of temperature occurs).
4 The halting criterion (stopping the search).

There are no hard and fast rules for determining these criteria and to some extent it is largely a process of trial and error. In this study an initial starting temperature of 1,000 was used and a cooling rate of $0.99 \%$. The maximum number of iterations was set at 10,000 . For some trees starting temperature was increased to 10,000 . The initial starting parameters are chosen using a random number generator and the search space was restricted by putting limits on the value of the parameters. These limits were $0.1<c_{1}<1.0$ and $0.5<c_{2}<5.0$.

### 3.8.2.3 Non linear regression

Parameters were also estimated using non linear regression techniques. The routine used was programmed using an algorithm developed by Buys and von Gadow (1987). Starting values were those parameter values found through either the raster search or simulated annealing. The routines were programmed to run sequentially. As with simulated annealing, this routine used the sum of squared differences between observed and predicted annual values of relative volume increment to optimise parameter combinations. To do this the annual estimation method of Gerold and Römisch (1977) was included in the programme. It was not possible to compare results using statistical packages such as SPSS unless the annual interpolations were omitted from the analysis.

### 3.8.2.4 Combined analysis

Both simulated annealing and non linear regression were used to estimate parameters of individual stem analysis trees. They were also used to analyse the rapid method trees as a group (RPM), all stem analysis trees from a given site simultaneously (STAND) and rapid method and stem analysis trees from a given site together (COMB).

### 3.8.2.5 Variations

In the estimation of parameters only $c_{1}$ and $c_{2}$ were evaluated, $c_{3}$ and $c_{4}$ being considered to be constant and set to 0.4 and zero respectively. However the analyses were also carried out using different values of $c_{3}$ to investigate the effect this would have on the value of $c_{1}$ and $c_{2}$ and on the fit of predicted values to observed. Several attempts were also made to simultaneously estimate $c_{1}, c_{2}$ and $c_{3}$ in SPSS using data for $p_{\mathrm{V} 10}$ without the Gerold and Römisch interpolation. In the initial analyses all the data from every year from age 10 were used. In order to see if an improvement in model fit could be obtained the data sets for some trees were systematically modified and reanalysed. Various approaches were tried including starting at later ages, stopping at younger ages, progressively deleting a year from the beginning or end of the data set, and using intervals other than one year.

To determine whether values of transformed time, other than 10 , are appropriate for Sitka spruce this was also varied for several trees. One attempt was made to give a tree an assumed age to try and obtain better parameterisation.

### 3.9 Volume model

Parameters obtained from the various estimation methods were inserted into a spreadsheet which automatically calculated observed and predicted volume, height, diameter and $1-p_{V}$ development over time for the tree being studied. This spreadsheet gave numerical and visual indication of the bias in the model for the three variables.

### 3.10 Relationships with environmental variables

Basic environmental data were extracted from the Ecological Site Classification (Ray, 2001) and these are listed below:

1 Elevation (metres).
2 Accumulated temperature (day degrees above $5^{\circ} \mathrm{C}$ ).
3 Moisture deficit (mm).
4 DAMS.
5 Continentality.
6 Soil moisture regime.
7 Soil nutrient regime.
DAMS (Detailed Aspect Method of Scoring) is a measure of exposure (Quine and White, 1993, 1994).

Parameter values were regressed against these data to assess potential relationships. They were also regressed against yield class from SCDB and estimated from inventory data. The regressions were done for single environmental variables and also as backward multiple regression to determine which variables had greatest influence on the parameters.

## 4

## RESULTS

### 4.1 Rapid method

### 4.1.1 Growth parameter $c_{1}$

Values of the growth parameter $c_{1}$, for rapid method trees plotted against individual tree volume, are shown in Fig. 4.1. The value of $c_{2}$ was kept constant at 1 and $c_{3}$ at 0.4 . There is a wide range of $c_{1}$ values, the maximum being 0.7312 and the minimum 0.0579 . The range is much wider at smaller volumes and curves for the $95^{\text {th }}$ and $5^{\text {th }}$ percentiles converge as volume increases, which is suggestive of a limiting range of values. The range of $c_{1}$ values for a tree with a volume of $2.5 \mathrm{~m}^{3}$ is 0.1338 to 0.2693 . For a tree with volume only $0.1 \mathrm{~m}^{3}$ the corresponding values are 0.0888 to 0.5838 and the lower percentile shows a slight falling trend with decreasing volume. The central trendline represents average values and was estimated using equation 3.10. The asymptote is only 0.0881 but the estimated $c_{1}$ value of the tree with volume $2.5 \mathrm{~m}^{3}$ is 0.2005 . The position of both upper and lower asymptotes must be treated with caution as there is a paucity of data from better sites, with greater volume throughout the diameter range of the stand, and also of large volume trees from poorer sites. In estimating the upper percentile there are only few data at volumes over $1.5 \mathrm{~m}^{3}$ and the lower percentile uses only trees up to that volume and is extrapolated beyond this.

Fig. 4.2 shows the distribution of $c_{1}$ values plotted against individual tree volume following transformation of the data. There is a much more restricted spread of values compared to the raw data and though the maximum is higher at 0.9657 the minimum is also higher with a value of 0.1468 . A negative correlation with volume is more obvious than with the raw data and curves for the $5^{\text {th }}$ and $95^{\text {th }}$ percentiles were fitted using equation 3.9 rather than a logarithmic curve. A similar caution applies to the percentile curves as with the raw data regarding the lack of data for certain tree sizes. The asymptotes of the three curves are $0.1533,0.1939$ and 0.2374 for the $5^{\text {th }}$ percentile, $95^{\text {th }}$ percentile and average respectively. The range of $c_{1}$ values for the tree with volume $2.5 \mathrm{~m}^{3}$ is, for the $5^{\text {th }}$ percentile, 0.1533 and for the $95^{\text {th }} 0.2662$. The average figure is 0.2004 .


Figure 4.1 Distribution of $c_{1}$ values for rapid method trees when plotted against volume. The $5^{\text {th }}$ and $95^{\text {th }}$ percentiles are shown and give an indication of upper and lower limits of values.


Figure 4.2 Distribution of $c_{l}$ values after data smoothing. The $5^{\text {th }}$ and $95^{\text {th }}$ percentiles were modelled in SPSS and the equations are given in the text. Only data up to volume class 1.7 were used for the lower percentile and up to 2.5 for the upper percentile.
4.1.2 Trends in $c_{1}$ values within sites for different values of $c_{2}$

The effect of alternative values of $c_{2}$ on the value of $c_{1}$ for any given site is illustrated in Fig. 4.3. Average trendlines were fitted to transformed data and so the curve for $c_{2}=1.0$ is the same as that in Fig 4.2. Asymptotic values of $c_{1}$ are 0.1509 and 0.0545 for $c_{2}$ equal to 0.5 and 1.5 respectively. The corresponding values for a tree with a volume of $2.5 \mathrm{~m}^{3}$ are 0.1842 and 2.685 . Because of the exponential nature of the functions the value of $c_{1}$ is much more sensitive to change in $c_{2}$ values below 1 than above and there is little change in $c_{1}$ when $c_{2}$ is greater than 5 . These patterns are similar to the effect of maintaining $c_{2}$ at 1 but altering $c_{3}$ to 0.3 or 1 .


Figure 4.3 Variation in $c_{1}$ value with differing $c_{2}$ value. Trend lines derived from transformed data.

### 4.1.3 Distribution of $c_{1}$ values on individual sites

From Figs. 4.1 and 4.2 it is difficult to discern individual patterns that show both within and between site variation in $c_{1}$ value. Figs. 4.4 to 4.7 show typical patterns, plotted against diameter (dbh) for selected sites. The remainder of the sites are illustrated in appendix 1. In these diagrams the trendlines for both raw and transformed data are estimated using equation 3.10.


Figure 4.4 Distribution of $c_{1}$ at site CLG8 plotted against diameter. Solid squares (dbh:c $c_{l}$ ) are raw data, open circles are transformed data (dbh:clreg). The solid trendline is for raw data, the dashed line for the transformed data.

Fig. 4.4 illustrates data for CLG8. The raw values of $c_{1}$ are widely scattered, though there is an overall negative correlation with tree size. The highest values of $c_{1}$ are generally for the smallest trees and there is an initial steep decline as size increases. The curve then flattens though in this case the asymptote is not reached within the data range. The values for transformed data exhibit a much smoother distribution with obvious decrease in value with increasing tree size. The two trend lines are similar. The estimated value of $c_{1}$ for a tree with dbh of 10 cm from the transformed data trendline (regtrend) is 0.4150 and the asymptote is 0.1891 . The tree with mean basal area has an estimated $c_{1}$ value of 0.2194 and $50 \%$ of trees have values of 0.2350 or less. Sites CLG9, CLG10, and to some extent PEN1 have similar patterns.

Several sites, whilst exhibiting an overall negative correlation between $c_{1}$ and tree size, have trendlines that diverge more from each other than CLG8. Fig. 4.5 illustrates the case of GWY7 in which the two trendlines cross. The curve for the raw data has a shallower slope than that of the transformed data and a much lower asymptote, not reached within the data range. The asymptotes are 0.1278 for the raw data and 0.2003 for the transformed values. Trees with diameter 40 cm are estimated to have $c_{1}$ values of 0.1660 and 0.2003 respectively. The value of $c_{1}$ for the tree with mean basal area calculated from the transformed data is 0.3006 and $50 \%$ of trees have values less than 0.3346 .


Figure 4.5 Distribution of $c_{1}$ at site GWY7 plotted against diameter. Solid squares (dbh:c ${ }_{l}$ ) are raw data, open circles are transformed data (dbh:clreg). The solid trendline is for raw data, the dashed line for the transformed data.

Particularly on those poor sites, with small trees throughout the diameter range, the raw data are very widely scattered with no obvious trend between the raw data and tree size. Fig. 4.6 illustrates this using data from GWY8. The unusual pattern of the trendline for the raw data is caused by a single data point for the smallest tree. For other sites, for example, GWY5 and GFS1 the trendline does not have the steep rise and for GWY3 even falls slightly with increasing tree size. The transformed data still produce a smooth curve despite the erratic nature of the raw data. If values are estimated from the
transformed trendline, the tree with mean basal area has a $c_{1}$ value of 0.1864 and a tree with a dbh of $22 \mathrm{~cm}, 0.1694$, which is the asymptote. Fifty percent of the trees are estimated to have a $c_{1}$ value of 0.1992 or less.


Figure 4.6 Distribution of $c_{1}$ at site GWY8 plotted against diameter. Solid squares (dbh:c ${ }_{l}$ ) are raw data, open circles are transformed data (dbh:clreg). The solid trendline is for raw data, the dashed line for the transformed data.


Figure 4.7 Distribution of $c_{1}$ at site BAD2 plotted against diameter. Solid squares (dbh:c $c_{l}$ ) are raw data, open circles are transformed data (dbh:clreg). The solid trendline is for raw data, the dashed line for the transformed data.

The example of BAD2 is illustrated in Fig. 4.7. In this and CLG12 the two trend lines are completely separate. In both situations the transformed values are nearly all greater than the raw values and the asymptotes of the two lines are very different, being 0.1917 for the raw data and 0.2953 for the transformed data. This gap is slightly narrower for the largest tree, remaining at 0.2953 for the transformed data and 0.2121 for the raw data.

### 4.1.4 Distribution of $c_{1}$ values by site

Fig. 4.8 shows a typical distribution of $c_{1}$ values between sites using the example of Clocaenog forest. Four of the stands, although of different ages and yield class, exhibit a narrow range of minimum $c_{1}$ value. CLG10 is widely separated from these four and in fact has a much higher minimum $c_{1}$ value than any other site. Any distinct pattern is even less clear in Gwydyr Forest, where one of the the fastest growing sites, GWY3 has the second lowest $c_{1}$ value. Of those sites on the Llŷn and Anglesey, UPM2, with a yield class of only 14 , has similar $c_{1}$ values to GFS1 with yield class 20. At Bryn Arau Duon the poorest site, BAD 2 has a higher $c_{1}$ value than BAD 1 .

The result of applying site specific $c_{2}$ values is illustrated in Fig 4.9. These site specific values are given in table 4.6 in section 4.3.1.2. The effect is unpredictable. In Clocaenog three sites now have similar values and CLG10 is not so isolated. On the other hand CLG9, with relatively high yield class has a slightly lower value of $c_{1}$ than the poorest site, CLG12. In Gwydyr forest the range of values of $c_{1}$ becomes narrower.


Figure 4.8 Pattern of $c_{l}$ values by site at Clocaenog Forest


Figure 4.9 Pattern of $c_{1}$ values, when $c_{2}$ is variable, by site at Clocaenog Forest

### 4.1.5 Alternative measures of site $c_{1}$ value

Tables 4.1 and 4.2 summarise values of the growth parameter $c_{1}$ that could possibly be used to indicate potential values for a given site. In table $4.1 c_{2}$ is constant and in table 4.2 is given a site specific value (section 4.3.1.2). Vol reg and dbh reg are asymptotic
values of $c_{1}$ when plotted against volume and dbh respectively. There is very close agreement between these values (Fig. 4.10) and all other values of $c_{1}$ are estimated from the diameter curve. The minimum value of $c_{1}$ is designated $\min c_{1}$ and is often lower than the asymptote. The values for the 100 largest diameter trees $\left(\mathrm{d}_{100} c_{1}\right)$ for BAD1 and 2 are estimated from a regression against dbh reg which is shown in Fig. 4.11. As suggested in section 4.1.4 there is little correspondence between $c_{1}$ values estimated with constant $c_{2}$ and with site specific $c_{2}$ (Fig. 4.12).

Table 4.1 Alternative estimates of site $c_{l}$ value from temporary sample plots. $d_{100}$ reg for BAD1 and BAD2 estimated from a regression of asymptotic $c_{1}$ against $d_{100} c_{1}$.

|  | vol reg | dbh reg | $\mathrm{d}_{100}$ raw | $\mathrm{d}_{100}$ reg | $\mathrm{d}_{\mathrm{g}} c_{1}$ | $\min c_{1}$ | YC |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CLG8 | 0.1911 | 0.1891 | 0.1947 | 0.1903 | 0.2194 | 0.1854 | 14 |
| CLG9 | 0.1825 | 0.1902 | 0.2027 | 0.1907 | 0.2123 | 0.1712 | 21 |
| CLG10 | 0.3070 | 0.3073 | 0.3126 | 0.3119 | 0.3567 | 0.3054 | 30 |
| CLG11 | 0.1645 | 0.1618 | 0.1611 | 0.1637 | 0.1883 | 0.1606 | 17 |
| CLG12 | 0.1711 | 0.1686 | 0.1459 | 0.1689 | 0.2028 | 0.1645 | 6 |
| GWY3 | 0.1725 | 0.1737 | 0.1876 | 0.1737 | 0.1768 | 0.1718 | 22 |
| GWY4 | 0.1605 | 0.1610 | 0.1738 | 0.1610 | 0.1640 | 0.1593 | 12 |
| GWY5 | 0.2158 | 0.2173 | 0.2268 | 0.2174 | 0.2237 | 0.2150 | 23 |
| GWY6 | 0.1847 | 0.1763 | 0.1916 | 0.1767 | 0.2379 | 0.1539 | 10 |
| GWY7 | 0.2018 | 0.2003 | 0.2040 | 0.2013 | 0.2716 | 0.1787 | 17 |
| GWY8 | 0.1923 | 0.1919 | 0.1962 | 0.1920 | 0.2091 | 0.1873 | 6 |
| PEN1 | 0.2144 | 0.2144 | 0.2138 | 0.2187 | 0.2557 | 0.2133 | 24 |
| UPM1 | 0.1485 | 0.1391 | 0.1613 | 0.1504 | 0.1779 | 0.1468 | 16 |
| UPM2 | 0.1847 | 0.1867 | 0.2144 | 0.1951 | 0.1951 | 0.1822 | 14 |
| GFS1 | 0.1910 | 0.1996 | 0.1998 | 0.1996 | 0.2127 | 0.1866 | 18 |
| BAD1 | 0.1727 | 0.1721 |  | 0.1745 |  | 0.1678 | 20 |
| BAD2 | 0.2950 | 0.2953 |  | 0.2972 |  | 0.2754 | 6 |



Figure 4.10 Correspondence between asymptotic $c_{l}$ values when regressed against both volume and dbh.


Figure 4.11 Regression of dbhreg $c_{1}$ and $d_{100} c_{1}$

Table 4.2 Asymptotic and $d_{I O 0} c_{1}$ values from temporary sample plots with site specific $c_{2}$.

|  | $c_{2}$ | vol reg | dbh reg | $\mathrm{d}_{100}$ raw | $\mathrm{d}_{100}$ reg | $\mathrm{d}_{\mathrm{g}} c_{1}$ | $\min c_{1}$ | YC |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CLG8 | 0.40 | 0.2903 | 0.2872 | 0.2957 | 0.2890 | 0.3332 | 0.2186 | 14 |
| CLG9 | 3.00 | 0.1554 | 0.1620 | 0.1725 | 0.1624 | 0.1807 | 0.1458 | 21 |
| CLG10 | 1.25 | 0.2830 | 0.2833 | 0.2882 | 0.2876 | 0.3288 | 0.2816 | 30 |
| CLG11 | 0.30 | 0.2794 | 0.2749 | 0.2736 | 0.2781 | 0.3199 | 0.2728 | 17 |
| CLG12 | 1.40 | 0.1629 | 0.1606 | 0.1392 | 0.1608 | 0.1931 | 0.1566 | 6 |
| GWY5 | 1.70 | 0.1948 | 0.1962 | 0.2047 | 0.1962 | 0.1972 | 0.1936 | 23 |
| GWY6 | 0.70 | 0.2105 | 0.2009 | 0.2184 | 0.2014 | 0.2683 | 0.1754 | 10 |
| GWY7 | 0.75 | 0.2233 | 0.2216 | 0.2257 | 0.2228 | 0.3006 | 0.1978 | 17 |
| GWY8 | 2.40 | 0.1698 | 0.1693 | 0.1732 | 0.1695 | 0.1846 | 0.1653 | 6 |
| PEN1 | 0.40 | 0.2926 | 0.2927 | 0.2918 | 0.2985 | 0.3489 | 0.2911 | 24 |
| UPM1 | 0.35 | 0.2369 | 0.2089 | 0.2574 | 0.2399 | 0.2837 | 0.2342 | 16 |
| UPM2 | 0.30 | 0.2922 | 0.2954 | 0.2908 | 0.2956 | 0.3086 | 0.2882 | 14 |



Figure 4.12 Relationship between $c_{1}$ with $c_{2}=1$ and $c_{1}$ when $c_{2}$ is variable

### 4.1.6 Relationship between $c_{1}$ and yield class

The relationships between the selected estimates of site $c_{1}$ (for $c_{2}=1$ ) and yield class are shown in Figs. 4.13 and 4.14. Although there is an apparent positive relationship between site and growth parameter the coefficient of determination is very low. Except for the case of $\mathrm{d}_{\mathrm{g}} c_{1}, \mathrm{r}^{2}$ values are below 0.1 . With the latter $\mathrm{r}^{2}$ rises to only 0.282 . The sites with low yield class appear to be anomalous and both BAD1 and BAD2 are missing from the $\mathrm{d}_{\mathrm{g}}$ data set. The high $c_{1}$ value estimated for CLG10 is isolated from the rest of the data. Values of dbh reg $c_{1}$ and $\mathrm{d}_{100} c_{1}$ have similar patterns.


Figure 4.13 Relationship between $c_{I}$ and yield class (YC) for minimum values of regression $c_{l}$


Figure 4.14 Relationship between $c_{1}$ and yield class (YC) for $c_{l}$ values of the mean diameter tree ( $d_{g}$ )

Relationships between $c_{1}$ and yield class for variable values of $c_{2}$ are illustrated in Figs. 4.15 and 4.16. Although $\mathrm{r}^{2}$ values are low this appears to be a little stronger than when $c_{1}$ is constant across all sites. All the alternatives show a similar pattern.


Figure 4.15 Relationship between $c_{I}$ and yield class (YC) for minimum values of regression $c_{1}$ when $c_{2}$ is variable.


Figure 4.16 Relationship between $c_{1}$ and yield class (YC) for $c_{1}$ values of the mean diameter tree ( $d g$ ) when $c_{2}$ is variable

### 4.1.7 Variation in $c_{1}$ with age

Values of $c_{1}$ calculated for individual years using stem analysis data are illustrated in Fig. 4.17. This shows that, rather than being constant throughout the life of a tree, $c_{1}$ decreases with age. At younger ages the pattern is very erratic and some trees may show a rising trend following a sharp decline in the years before age 20. With increasing age $c_{1}$ appears to reach a constant level and two trees over 60 years of age (from Artist's Wood and Coed y Brenin) illustrate this.


Figure 4.17 Relationship between $c_{1}$ and age from a sample of stem analysis trees. The heavy line was estimated using data from two trees aged 80 and 76 years from Coed y Brenin and Artist's Wood.

### 4.1.8 Estimates of volume increment and $c_{1}$

Current volumes of rapid method trees calculated using the average diameter method described in section 3.4.1 are compared with those from stem analysis in Fig. 4.18. There is good correspondence between the two. Values for volume from 10 years ago are also shown in Fig. 4.18. Once again there is a good linear relationship between the two despite one or two more obvious differences. There is however a slight underestimation in volume from ten years ago using the average diameter technique compared to stem analysis and this increases with increasing volume.

The effect of the bias in estimation of volume from ten years ago is an overestimation in relative volume increment using the rapid method compared to stem analysis. This means that $c_{1}$ values are underestimated and this is illustrated in Fig. 4.19. The pattern is somewhat uneven and there is a lack of data for larger volumes. Differences are very large at lower volumes and there are some very low $c_{1}$ values calculated using the rapid method.


Figure 4. 18 Comparison of $c_{1}$ of individual trees calculated by stem analysis and average diameter method. $\left(v_{t}\right.$ and $v_{t-10}$ are current volume and volume 10 years ago; rpm refers to rapid method trees and sa to stem analysis trees).


Figure 4.19 Comparison of $c_{1}$ of individual trees calculated by stem analysis and average diameter method

### 4.2 Stem analysis trees

### 4.2.1 Estimation techniques

Values of $c_{1}$ and $c_{2}$ estimated using simulated annealing and non linear regression are shown in Figs. 4.20 and 4.21. Both methods used the same criterion to optimise parameter estimation and, apart from a few obvious exceptions, there was little difference in the results from the two methods. The grid search method used a different optimisation criterion and gave different results, occasionally with $c_{2}$ values in excess of 30. If such high values were used as start values for the regression routine the method would fail to give a result. The simulated annealing routine could be set to give upper and lower limits to both $c_{1}$ and $c_{2}$ but then the optimum values might not be found. In Figs. 4.20 and $4.21 c_{2}$ values below 0.5 and above 5.0 are omitted.


Figure 4.20 Comparison of values of $c_{1}$ estimated from simulated annealing (SimAnn) and non linear regression (NLR).


Figure 4.21 Comparison of values of $c_{2}$ estimated from simulated annealing (SimAnn) and non linear regression (NLR). Values of $c_{2}$ greater than 5 and less than 0.5 have been omitted.

### 4.2.2 Parameter values

Values of both $c_{1}$ and $c_{2}$, estimated using non-linear regression, from stem analysis trees are shown in Figs. 4.22 and 4.23. Detailed figures are provided in appendix 2. The majority of $c_{1}$ values ( $80 \%$ ) lie between 0.125 and 0.375 . Of the remainder eight are
greater than 0.525 of which three are greater than 1.0. If these larger values are not considered then $c_{1}$ is clustered around the 0.25 class. Values of $c_{2}$ follow a similar pattern, $87.5 \%$ between the 0 and 5 classes. Only three values are above the 9.75 class. The most frequent value is 1.5 and overall $80 \%$ of values lie between the 0.5 and 3.5 classes inclusive.


Figure 4.22 Distribution of $c_{l}$ values of 60 stem analysis trees in 0.05 classes.


Figure 4.23 Distribution of $c_{2}$ values of 60 stem analysis trees in 0.5 classes.


Figure 4.24 Relationship between $c_{1}$ and $c_{2}$ values of stem analysis trees, values estimated from non linear regression (NLR).

Values of $c_{1}$ and $c_{2}$ of stem analysis trees are shown in Fig.4.24. Values of $c_{1}$ greater than 0.5 and values of $c_{2}$ above 5.0 have been omitted. There is a weak negative correlation but there is a wide spread of $c_{2}$ values for all values of $c_{1}$ though this range decreases with increasing $c_{1}$. It is possible to designate individual trees into arbitrary classes based on the values of both $c_{1}$ and $c_{2}$ and Fig.4.24 is sub-divided in such a way. If values are considered high, medium or low then the majority of values fall in the class medium-medium $\left(c_{1}-c_{2}\right)$ and medium-high.

### 4.2.3 Volume development of individual trees

Models of individual tree growth are shown in Fig. 4.25. The solid line represents the tree which would have average parameter values, these being 0.2050 and 1.922 for $c_{1}$ and $c_{2}$ respectively. The pattern of growth for individual trees varies considerably and the average values cannot be used to model all trees. Fig.4.26 illustrates in more detail the model results compared to the individual tree observations for CLG10. Diagrams for other sites are shown in appendix 3 .


Figure 4.25 Volume growth of all stem analysis trees. The solid line represents average development using parameters derived from all trees and a starting volume of average volume at age 10.

Development over age of the inverse of the growth multiplier ( $1-p_{\mathrm{V}}$ ), volume and relative volume bias are shown in Figs. 4.27 to 4.33 for a range of parameter values and tree sizes. These represent a selective sample of typical patterns. Nearly all trees show erratic patterns of $1-p_{\mathrm{V}}$ in the first 10 to 20 years of life after which the growth pattern tends to fluctuate only slightly. All trees demonstrate an increase in $r^{2}$ value for the volume model compared to that of the inverse of the multiplier. This is small for CLG10 but extreme for GWY4-3. The model for CLG10-3 exhibits very little bias throughout the growth period whereas that for GWY4-3 reaches a peak of 2.8 and is still at 0.5 at the time of sampling. Projected volume at age 100 for this tree is $25.5 \mathrm{~m}^{3}$, reflecting the very small $c_{1}$ that has been given to it. In this particular case neither simulated annealing nor non linear regression could find an optimum value for the parameters. Most trees do not show such extreme bias and many have maximum and minimum bias of no more than $\pm 0.10$ once the initial growth phase is over. PEN1-7, for example has a maximum bias of 0.33 , in the early period of fluctuation, but this does not exceed 0.10 after about 20 years. In this case the high $c_{1}$ value gives an estimated volume of $7.4 \mathrm{~m}^{3}$ at age 100 . A similar volume at 100 is projected for CLG12-6 a tree from a checked site whose current volume is only $0.24 \mathrm{~m}^{3}$ compared to the $2.7 \mathrm{~m}^{3}$ of

PEN1-7. The $c_{1}$ value of CLG12-6 is only 0.1249 . GWY8-1 is another tree from a checked site. Even though it has a $c_{1}$ value close to the average of all trees its projected volume at age 100 is only $0.3 \mathrm{~m}^{3}$. The bias shown by predicted values is always within $\pm 0.10$. GWY8-919 has a very similar pattern of growth.


Figure 4.26 Patterns of tree growth of individual trees for CLG10. The large symbols are observed values and the narrow lines are modelled values. The heavy line represents the tree with average parameter values.

CLG11-1 and PEN1-8 are suppressed trees whose growth seems to be slowing. The estimated parameters for the trees are very different. CLG11-1 has a low $c_{1}$ value and a high $c_{2}$ value, PEN1-8 the opposite. Both trees have similar volumes but the former is projected to have a volume of $5.0 \mathrm{~m}^{3}$ at age 100 compared to only $0.5 \mathrm{~m}^{3}$ for the latter. CLG11-1 has a high negative bias at age 30 which is reduced to only 0.001 at the end of the sample period. This pattern is similar to one of the two older trees (ATW1-1947) which were sampled.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at 100 yrs | $\min$ bias | $\max$ bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.2570 | 1.8660 | 0.9771 | 0.9998 | $13.3 \mathrm{~m}^{3}$ | -0.027 | 0.048 | 0.002 |

Figure 4.27 The inverse of the growth multiplier ( $1-p_{V}$ ), volume development and volume bias for tree CLG10-3. In the upper two diagrams points are observed and lines modeled values.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at $100 y r s$ | $\min$ bias | $\max$ bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.1490 | 4.6427 | 0.7370 | 0.9378 | $5.0 \mathrm{~m}^{3}$ | -0.272 | 0.130 | 0.001 |

Figure 4.28 The inverse of the growth multiplier $\left(1-p_{V}\right)$, volume development and volume bias for tree CLG11-1.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at 100 yrs | $\min$ bias | $\max$ bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.1000 | 0.6308 | -0.4007 | 0.6255 | $25.5 \mathrm{~m}^{3}$ | 0.489 | 2.792 | 0.489 |

Figure 4.29 The inverse of the growth multiplier ( $1-p_{V}$ ), volume development and volume bias for tree GWY4-3.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at 100 yrs | min bias | max bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.2044 | 8.7066 | 0.8896 | 0.992 | $0.3 \mathrm{~m}^{3}$ | -0.096 | 0.027 | -0.003 |

Figure 4.30 The inverse of the growth multiplier ( $1-p_{V}$ ), volume development and volume bias for tree GWY8-1.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at $100 y r s$ | min bias | max bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.2910 | 0.5602 | 0.8701 | 0.9942 | $7.4 \mathrm{~m}^{3}$ | -0.057 | 0.329 | 0.044 |

Figure 4.31 The inverse of the growth multiplier (1-p $v_{V}$, volume development and volume bias for tree PEN1-7.




| $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at $100 y r s$ | $\min$ bias | $\max$ bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.4576 | 0.5901 | 0.8631 | 0.9894 | $0.5 \mathrm{~m}^{3}$ | -0.068 | 0.460 | 0.089 |

Figure 4.32 The inverse of the growth multiplier ( $1-p_{V}$ ), volume development and volume bias for tree PEN1-8.

CYB4





| site | $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at 100 yrs | $\min$ bias | max bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CYB4 | 0.1878 | 4.5353 | 0.9264 | 0.951 | $14.5 \mathrm{~m}^{3}$ | -0.079 | 0.303 | -0.049 |
| ATW1- <br> 1947 | 0.1686 | 4.06 | 0.93427 | 0.9800 | $20.5 \mathrm{~m}^{3}$ | 0.238 | 0.053 | 0.037 |

Figure 4.33 The inverse of the growth multiplier ( $1-p_{V}$ ), volume development and volume bias for trees CYB4 and ATW11947.

The growth patterns of the two oldest trees analysed are compared together in Fig. 4.33. Although the two trees have similar $c_{2}$ values the differences in $c_{1}$ value are sufficient to give them very different patterns of growth. CYB4 exhibits positive high bias at about age 35 but after this bias falls to a fairly steady -0.05 . By comparison ATW1-1947 has fluctuating but low bias in the first 30 years which then falls to -0.24 at age 45 . A value of only 0.037 at the end of the sample period does not mask the fact that bias is showing
a strong upward trajectory at this point. Projected volume at age 100 is $20.45 \mathrm{~m}^{3}$ for ATW1-1947 but only $14.5 \mathrm{~m}^{3}$ for CYB4. A careful examination of the observed data suggests that growth of ATW1-1947 may be slowing down whereas that of CYB4 is being maintained.

Fig. 4.34 compares volume projection for ATW1-1947 using parameters derived from analysis of 5 year and 10 year interval data. It also illustrates the application of 10 year derived parameters to an annual prediction model. The estimated value of $c_{1}$ is similar for the 5 and 10 year interval data and is slightly higher than when annual data are analysed. The overall pattern of growth and bias values for all three models are similar though for the wider interval data final bias remains negative and volume projection to age 100 is $18.2 \mathrm{~m}^{3}$ for 5 year intervals and $18.5 \mathrm{~m}^{3}$ for 10 year intervals. When 10 year parameters are applied in an annual prediction the pattern remains similar to that of the ten year prediction model. The parameter values of the models are given in table 4.3

Table $4.3 \begin{aligned} & \text { Parameter values for } 5 y r \\ & \text { ATW1-1947 }\end{aligned}$

| model | $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at 100 yrs | min bias | max bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 5 yr | 0.1736 | 3.8018 | 0.9451 | 0.9579 | $18.2 \mathrm{~m}^{3}$ | -0.269 | 0.050 | -0.062 |
| 10 yr | 0.1743 | 3.4248 | 0.9556 | 0.9652 | $18.5 \mathrm{~m}^{3}$ | -0.200 | 0.025 | -0.010 |

Fig 4.35 demonstrates how the model can be improved if the data are split and different sections analysed separately. In this case the data for ATW1-1947 were analysed for a period from 10 to 29 years of age then from 29 to 76 years. This point was found partly through examination of the pattern of the data and trial and error. The parameters are given in table 4.4. There is a marked increase in $c_{1}$ value and a corresponding decrease in that of $c_{2}$ for the second period. When the two models are combined the extremes in bias are reduced to 0.046 and -0.051 and volume at 100 years is estimated to be only $15.1 \mathrm{~m}^{3}$.

Table 4.4 Parameter values for 5yr and $10 y r$ interval data for tree ATW1-1947

| period | $c_{1}$ | $c_{2}$ | $r^{2}\left(1-p_{v}\right)$ | $r^{2}(v)$ | $v$ at $100 y r s$ | $\min$ bias | max bias | final bias |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $10-29$ | 0.1750 | 3.7932 | 0.9059 | 0.9987 | $17.0 \mathrm{~m}^{3}$ | -0.052 | 0.046 | -0.002 |
| $29-76$ | 0.2363 | 0.3835 | 0.9517 | 0.9993 | $14.9 \mathrm{~m}^{3}$ | -0.036 | 0.033 | -0.003 |
| $10-76$ |  |  | 0.9695 | 0.9994 | $15.1 \mathrm{~m}^{3}$ | -0.051 | 0.046 | -0.009 |



Figure 4.34 Comparison of the volume prediction for tree ATW1-1947 using parameters estimated from 5 and 10 year interval data. On the right hand side parameters from the 10 year interval data are applied to an annual prediction model.


Figure $4.35 \quad$ Volume prediction for tree ATW1-1947 after splitting the data set and using a combination of parameters.

### 4.3 Site specific parameter values

### 4.3.1 Alternative estimates of site specific parameters

### 4.3.1.1 Values of $c_{1}$

Fig. 4.36 illustrates the range of values for stand $c_{1}$ obtained from analysis of both rapid method and stem analysis trees. The actual values are given in table 4.5. In most cases there is wide variation between rapid method and stem analysis values and they are not correlated with each other (Fig. 4.37). Only CLG10 shows any similarity in value between the three methods. In most cases the rapid method value is greater than that from stem analysis trees, CLG9, GFS1, BAD1 and BAD2 being the exceptions. For some sites one or other method would not give a parameter value. Rapid method values tended to be quite high, ranging from 0.1456 to 0.3690 . Except for CLG10, values for stem analysis trees are markedly lower, ranging in value from 0.1260 to 0.3268 .


Figure 4.36 Stand values of $c_{I}$ estimated from non linear regression from rapid method and stem analysis for 15 sites. Solid squares are rapid method trees, solid triangles are stem analysis trees and open circles are combined results. Results for CLG12, GWY6 and GWY8 could not be computed.

Table $4.5 \quad$ Values of $c_{1}$ from rapid method and stem analysis data estimated from non linear regression. ( $R P M=$ rapid method; STAND = stem analysis; $C O M B=$ combined data set $)$

|  | RPM | STAND | COMB | YC |
| :---: | :---: | :---: | :---: | :---: |
| CLG8 | 0.3690 | 0.2063 | 0.2427 | 14 |
| CLG9 | 0.2201 | 0.3001 | 0.2355 | 21 |
| CLG10 | 0.3269 | 0.3268 | 0.3213 | 30 |
| CLG11 | 0.3678 | 0.1963 | 0.2043 | 17 |
| CLG12 | 0.1456 |  | 0.1330 | 6 |
| GWY4 | 0.2786 | 0.1235 | 0.1908 | 12 |
| GWY6 | 0.3106 |  |  | 10 |
| GWY7 | 0.3063 | 0.2310 | 0.2397 | 17 |
| GWY8 | 0.1835 |  |  | 6 |
| PEN1 | 0.3457 | 0.2508 | 0.2471 | 24 |
| UPM1 | 0.3041 | 0.1260 | 0.1733 | 16 |
| UPM2 | 0.3309 | 0.1995 | 0.1980 | 14 |
| GFS1 | 0.2040 | 0.2501 | 0.2075 | 18 |
| BAD1 | 0.2005 | 0.4060 | 0.3738 | 20 |
| BAD2 | 0.2338 | 0.3523 | 0.2417 | 6 |



Figure 4.37 Comparison of the values of $c_{1}$ estimated from stem analysis trees (STAND) and rapid method trees (RPM)

When the data sets are combined estimated values of $c_{1}$ tend towards the lower value regardless of whether this was for the rapid method trees or stem analysis trees though overall stem analysis trees are more highly correlated with the combined values (Figs. 4.38 and 4.39). Maximum and minimum values of the combined data are 0.3213 and 0.1733 .


Figure 4.38 Comparison of the values of $c_{1}$ estimated from rapid method trees (RPM) and combined values (COMB)


Figure 4.39 Comparison of the values of $c_{1}$ estimated from rapid method trees ( $R P M$ ) and combined values (COMB)

### 4.3.1.2 Values of $c_{2}$

The range of values of $c_{2}$ are illustrated in Fig. 4.40 and given in table 4.6. As with $c_{1}$ values there is no clear relationship between rapid method and stem analysis results (Fig. 4.41). The rapid method trees generally have lower values than stem analysis trees. When the data are combined results are more closely related to stem analysis values (Figs. 4.42 And 4.43), though for four of the stands the combined value is higher than either of the others. For one stand it is lower. The maximum value is 6.9 and the minimum value is 0.29 .


Figure 4.40 Stand values of $c_{2}$ estimated from non linear regression from rapid method and stem analysis for 15 sites. Solid squares are rapid method trees, solid triangles are stem analysis trees and open circles are combined results. for CLG12, GWY6 and GWY8 could not be computed.

Table 4.6 Values of $c_{2}$ from rapid method and stem analysis data estimated from non linear regression. (RPM = rapid method; Stand $=$ stem analysis; $C O M B=$ combined data set; blanks indicate values that would not compute using simulated annealing and non linear regression.)

|  | RPM | STAND | COMB | YC |
| :---: | :---: | :---: | :---: | :---: |
| CLG8 | 0.3922 | 1.1707 | 0.9277 | 14 |
| CLG9 | 3.0476 | 1.1479 | 1.5941 | 21 |
| CLG10 | 1.2311 | 1.3128 | 1.3414 | 30 |
| CLG11 | 0.2899 | 1.2630 | 1.1899 | 17 |
| CLG12 | 1.4035 |  | 6.8502 | 6 |
| GWY4 | 5.0843 | 1.3574 | 0.7093 | 12 |
| GWY6 | 0.7017 |  |  | 10 |
| GWY7 | 0.7353 | 3.1275 | 2.9094 | 17 |
| GWY8 | 2.3978 |  |  | 6 |
| PEN1 | 0.4137 | 1.5811 | 1.6208 | 24 |
| UPM1 | 0.3305 | 1.9294 | 1.1146 | 16 |
| UPM2 | 0.2953 | 3.0085 | 3.0649 | 14 |
| GFS1 | 1.8399 | 2.5958 | 3.5369 | 18 |
| BAD1 | 2.4943 | 0.3495 | 0.3832 | 20 |
| BAD2 | 2.0550 | 2.5037 | 4.7375 | 6 |



Figure 4.41 Relationship between $c_{2}$ values from rapid method (RPM) and stem analysis trees (STAND)


Figure 4.42 Relationship between $c_{2}$ values from rapid method (RPM) and combined rapid method and stem analysis trees (COMB)


Figure 4.43 Relationship between $c_{2}$ values of stem analysis trees (STAND) and combined rapid method and stem analysis trees (COMB)

### 4.3.2 Relationship with yield class

Combined values of $c_{1}$ and $c_{2}$ were regressed against yield class for each site and the results are illustrated in Figs 4.44 and 4.45 . For values of $c_{1}$ there is a positive correlation though the $\mathrm{r}^{2}$ value is only 0.3695 . The values for BAD1 and BAD2 lie well above the regression line. For $c_{2}$ values there is a weak negative relationship with yield class, and the $r^{2}$ value is similar to that for $c_{1}$ values. However the regression line crosses the x axis within the range of the data at yield class 30 .


Figure 4.44 Combined rapid method and stem analysis values of $c_{l}$ compared to estimated yield class.


Figure 4.45 Combined rapid method and stem analysis values of $c_{1}$ compared to estimated yield class.

### 4.4 The effect of parameter $c_{3}$ and transformed age

### 4.4.1 Alternative values of $c_{3}$



Figure 4.46 Values of $c_{1}$ and $c_{2}$ for 16 stem analysis trees for three alternative values of $c_{3}$ (0.3, 0.4 and 1.0).

Fig. 4.46 illustrates the effect that using alternative values of $c_{3}$ has on values of $c_{1}$ and $c_{2}$. The overall effect is of rising $c_{1}$ values with increasing $c_{3}$ values and a corresponding fall in $c_{2}$ values. Three values of $c_{3}$ were used and a consistent pattern of $c_{2}$ variation is seen with a rapid fall between 0.3 and 0.4 then a more steady decline. The decline is steeper for higher values of $c_{2}$. The effect on $c_{1}$ is more varied, some trees showing little variation and others a distinct rising trend with increasing $c_{3}$. The rising trend tends to occur when $c_{1}$ is already quite high. Fig. 4.47 shows $r^{2}$ values of the relative volume increment curve for the same trees for the three different values of $c_{3}$. Thirteen of the sixteen trees show a slight decrease or no change in $r^{2}$ value with increasing $c_{3}$. For the
remaining trees there is a slight increase. The percentage change in $\mathrm{r}^{2}$ is at most 2.78 for tree BAD1-6 and only one other tree (CLG10-8) has a change in excess of $1 \%$.


Figure 4.47 Values of $r^{2}$ for 16 stem analysis trees for three alternative values of $c_{3}$ (0.3, 0.4 and 1.0).

### 4.4.2 Transformed age

Table 4.7 provides data on the influence transformed age has on parameter estimation of stem analysis trees. All the analyses were started from age 15. For three of the trees there is a rise in both $c_{1}$ and $c_{2}$ values with increasing value of age transformation. There is little difference in the $\mathrm{r}^{2}$, and standard errors and the patterns differ for each tree. In all cases $r^{2}$ is higher and standard error lower for an age transformation of 10 compared to 8.75 .

Table 4.7 Effect of altering transformed age on $c_{1}$ and $c_{2}$ values.

| TREE | TRANS AGE | $c_{1}$ | $c_{2}$ | SS | $\mathrm{r}^{2}$ | SE |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| PEN1-7 | 5 | 19.3800 | 0.0006 | 0.1755 | 0.8871 | 0.0231 |
|  | 8.75 | 0.8043 | 0.0871 | 0.1218 | 0.9179 | 0.0192 |
|  | 10 | 0.4485 | 0.2895 | 0.1202 | 0.9190 | 0.0191 |
|  | 12.5 | 0.3709 | 1.1366 | 0.1280 | 0.9141 | 0.0197 |
|  | 15 | 0.4014 | 3.5429 | 0.1623 | 0.8906 | 0.0222 |
|  | 5 | 0.0840 | 0.3103 | 0.0132 | 0.8870 | 0.0147 |
|  | 8.75 | 0.1443 | 2.0017 | 0.0136 | 0.8839 | 0.0149 |
|  | 10 | 0.1696 | 3.4896 | 0.1301 | 0.8889 | 0.0146 |
|  | 12.5 | 0.2296 | 9.7335 | 0.0121 | 0.8965 | 0.0141 |
|  | 15 | 0.3047 | 33.5368 | 0.0128 | 0.8906 | 0.0145 |
|  | 5 | 0.1980 | 0.1332 | 0.0020 | 0.9306 | 0.0097 |
|  | 8.75 | 0.2302 | 1.0554 | 0.0014 | 0.9510 | 0.0081 |
|  | 10 | 0.2617 | 1.7753 | 0.0012 | 0.9571 | 0.0076 |
|  | 12.5 | 0.3443 | 4.8727 | 0.0009 | 0.9672 | 0.0066 |
|  | 15 | 0.4607 | 14.3443 | 0.0008 | 0.9731 | 0.0060 |
| PEN1-3 | 5 | 0.0983 | 0.6099 | 0.0035 | 0.8666 | 0.0105 |
|  | 8.75 | 0.1861 | 4.3447 | 0.0035 | 0.8685 | 0.0104 |
|  | 9 | NO RESULT | 0.0034 | 0.8694 | 0.0104 |  |
|  | 10 |  |  | 0.8708 |  |  |

### 4.5 Variations with yield class and site variables

### 4.5.1 Effect of individual environmental variables.

The alternative estimates of site specific $c_{1}$ from both rapid method and combined values were regressed against environmental variables. The results showed only very slight if any relationships and in all cases $\mathrm{r}^{2}$ values were very low. In Fig 4.48 the results from the estimate of $c_{1}$ for the 100 thickest trees when $c_{2}$ is variable are shown. There are weak positive trends with age, accumulated temperature, soil moisture regime, soil nutrient regime and latitude (northing). These trends are not consistent between the different estimates of $c_{1}$. This inconsistency is also seen in Fig. 4.49 which illustrates the results for the combined rapid method and stem analysis data. Several of the trends are now reversed including those for age, accumulated temperature and elevation.


Figure 4.48 Relationships between $c_{1}$ of the thickest 100 trees when $c_{2}$ varies with site.


### 4.5.2 Multiple regression

Results of using multiple regression to investigate the relationship between parameter values and environmental variables are shown in Fig. 4.50 with the coefficients of the regression. Generally results were similar for all the alternative values estimated from the rapid method data with $r^{2}$ values between 0.45 and 0.5 . There were differences in the weight of the independent variables and there was no consistency in the order in which these were excluded in backward regression. As an example $\mathrm{d}_{100} c_{1}$ is illustrated. In this case accumulated temperature has a slight negative effect whereas moisture deficit a slight positive one. Results for parameter $c_{2}$ are shown in Fig. 4.51.


Figure 4.50 Plot of predicted $c_{l}$ values of the thickest one hundred trees against estimated $c_{1}$ values (constant $c_{2}$ ) using 9 site variables.


Figure 4.51 Plot of predicted $c_{2}$ values of average of the one hundred largest trees against estimated $c_{2}$ values with variable using 8 site variables. MD was excluded automatically during backward regression.

When site specific $c_{2}$ is also taken into account there is an increase in $r^{2}$ value. The positive relationship with moisture deficit remains though both accumulated temperature and elevation are automatically excluded. There is also a positive relationship with windiness. Results are shown in Fig. 4.52.


Figure 4.52 Plot of predicted $c_{l}$ values of average of the one hundred largest trees against estimated $c_{1}$ values with variable $c_{2}$ using 7 site variables. Elevation and AT were excluded automatically during backward regression.

Results for combined values of $c_{1}$ from rapid method and stem analysis data are shown in Figs. 4.53 and 4.54. A model using eight independent variables, including age, fits the data with an $r^{2}$ value of 0.8443 . If only moisture deficit, windiness, soil moisture regime and soil nutrient regime are used the $r^{2}$ value falls to 0.7288 (Fig 4.54). Three of the variables have a negative effect, only soil nutrient regime having a positive one.


| constant | age | gr1 | gr2 | ele | AT | MD | DAMS | SMR | SNR | r2 |
| :---: | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| -0.1996 | -0.0079 | -0.0002 | 0.0002 | 0.0018 |  | 0.0054 | -0.0167 | -0.0003 | 0.0242 | 0.8443 |

Figure 4.53 Plot of predicted $c_{l}$ values against combined rapid method and stem analysis $c_{1}$ values using 8 site variables. AT was excluded automatically during backward regression.


Figure 4.54 Plot of predicted $c_{I}$ values against combined rapid method and stem analysis $c_{1}$ values using 4 site variables.

### 4.5.3 Environmental variables and yield class.

Observed yield class was also regressed against environmental variables and results shown in Fig. 4.55. The coefficient of determination was 0.8659 . There was a positive effect with accumulated temperature, longitude (easting), soil nutrient regime and age. In backward regression reduction to only five and then four parameters reduced the $r^{2}$ value to 0.8444 (Fig. 4.56). In the four parameter model moisture deficit, soil moisture regime, soil nutrient regime and windiness were the independent variables in order of influence.


Figure 4.55 Plot of predicted yield class against observed yield class using 9 site variables.


Figure 4.56 Plot of predicted yield class against observed yield class using 4 site variables. The regression coefficients are given in Fig. 4.55.

## 5 DISCUSSION AND CONCLUSIONS

In broad terms this investigation has fulfilled its objectives and the methods described have proved appropriate for gathering increment data in a relatively short time. It has been possible to examine the variation in relative volume increment of Sitka spruce, both within and between different sites and from a wide variety of site types. Stem analysis techniques have supported the usefulness of the rapid method whilst highlighting some of the problems that need to be considered. Stem analysis has also demonstrated the flexibility of the growth multiplier approach to modelling individual tree growth. Although only 17 sites were sampled, possible links between model parameters and site variables were also found.

### 5.1 Rapid method

### 5.1.1 Sampling methodology

The rapid method proved a useful technique for quickly gathering increment data. The selective sampling seemed to be appropriate for describing the variation in parameter values across the dbh range and a generally negative relationship between $c_{1}$ and tree size was established for most sites. Even though values of $c_{1}$ for individual trees were widely scattered the data transformation clarified the general trend. The main exceptions were those sites which had been or were still largely in check or where there was difficulty in establishing plots on similar site conditions within the same stand.

Stem analysis confirmed that the method could be used to measure current volume with some confidence but that volume from ten years ago was underestimated.

Locating and measuring average diameter was straightforward, only hampered by factors that affect any inventory such as inability to get a tape under a felled tree. Where average diameter fell on a whorl it is recommended that similar approaches are used to the measurement of dbh and diameters taken above and below the true position and averaged. The value of coefficient $k$ in equation 3.2 does not seem to be critical. Values between 1.03 and 1.05 would result in diameter differences of less than $1 \%$, well within the expected measurement error in the field.

Establishing the position of average diameter from 10 years ago ( $\mathrm{d}_{\mathrm{q}-10}$ ) was more problematic for two main reasons. One was the occasional difficulty in estimating
height at 10 years ago. Although every effort was made to ensure correct counting back of whorls and side branches there were occasional doubts as to whether the true height had been found. This could be due to loss or breakage of leaders, slow and stunted growth of suppressed trees or the occurrence of lammas growth. Cutting discs and counting rings was avoided as far as possible as it was very time consuming in difficult cases and could also give ambiguous results. When the current leader broke during felling an estimate of the true length could be made by examining previous growth. Comparison with stem analysis data suggests that for the vast majority of trees the correct whorl was identified. The second source of error involves potential change in form factor over the ten year period. Again, however, stem analysis showed that this had varied by no more than $5 \%$ to $10 \%$ over the previous 10 years, in most cases. The protocol advises against the sampling of suppressed trees, presumably because of some of these problems. However when selecting smaller trees it was not always easy to discern the condition of the crown and once felled it was often not possible to select a replacement tree. Therefore all felled trees were measured as accurately as possible and sampled.

Identification of the ring position from ten years previously was, in most cases, not difficult. Sometimes it was useful to mark the position of rings prior to scanning as unexpected shadow effects could make interpretation difficult. The largest problems occurred with those trees that had been growing rapidly but were now being suppressed. Outer rings were very difficult to identify and were frequently missing, either in part or presumably also for the full circumference of the disc. In some situations the apparent tenth ring included years where growth had been much stronger leading to an underestimation of volume 10 years ago. Relative volume increment would then be overestimated giving unduly low $c_{1}$ values. Without the use of more accurate scanning and microscope work to identify rings there is little that can be done about this problem, especially when the rings are actually missing. As well as the problems with identifying height growth and position of $\mathrm{h}_{0-10}$ this suggests that suppressed trees ought not to be included in this type of analysis. The problem did not necessarily apply to small trees on checked sites where diameter increment, even when extremely small, can often be clearly identified. Larger trees generally presented no problems in ring identification.

Another source of potential error is the use of a bark function to establish the thickness of bark for the $\mathrm{d}_{\mathrm{q}-10}$ disc. Site specific functions were used, developed from both stem analysis and rapid method trees. There was evidence to suggest that even within sites different functions for large and small trees would give more accurate results. Although differences of less than $2 \%$ in diameter estimation were found when using a general or site specific function there is an effect on the value of $c_{1}$ and for smaller and younger trees this would merit further investigation.

### 5.1.2 Parameter values

There was a wide spread in the values of $c_{1}$ in the raw data, some of which may be unrealistically low, possibly due to some of the reasons identified in the previous section. Within any given site however a falling trend in values with increasing tree size is discernible. Transformation of the data narrowed the range in $c_{1}$ values and emphasised the negative within site trend. In broad terms this confirms the hypothesis that $c_{1}$ can be interpreted in terms of tree vitality whilst still allowing for potential competition effects, microsite variation and random fluctuations. The pattern of transformed data suggests that for trees larger than the tree of average basal area $c_{1}$ values are very similar whereas smaller trees appear to be suffering from increasing competition effects and have large $c_{1}$ values. Therefore when estimating stand $c_{1}$ the number of sample trees can be restricted to the larger trees in the stand and a suitable measure would be minimum $c_{1}$ of the transformed data or the average $c_{1}$ of the largest 100 trees per hectare. The asymptote of the curve is perhaps less suitable as it is frequently found beyond the range of the data.

There is greater difficulty in interpreting between site differences and no clear patterns were discernible even when $c_{2}$ was given a site specific value. Low yield class and therefore slow growing sites in particular gave ambiguous results with erratic but similar $c_{1}$ values across a wide range of diameters. Minimum $c_{1}$ values are frequently as large as the better sites. These sites were frequently those either in check or which had obviously been in check in the past. The check was generally due to waterlogging which was variable across the site and which could therefore lead to erratic growth. Those trees now coming out of check will be growing at a faster rate than previously, possibly approaching or exceeding much larger trees on better sites but in the same general location, for example CLG12 and CLG11. In the case of BAD2 a single large tree
appears to account for the shift in the position of the curve of transformed data as indicated in Fig. 5.1. These patterns suggest that low yielding sites in north and mid Wales even up to yield class 10 should be treated with caution if they are to be included in this type of study.


Figure 5.1 Comparison of estimated $c_{1}$ values for BAD1 if one tree is removed from the sample

The variety of site types available for investigation in north Wales does would then seem to become very restricted. Despite an extensive search of the sub-compartment data base very few high yielding sites of suitable age were found. There is therefore a gap in the data between yield class 20 and yield class 30 . On Forestry Commission land most sites are clustered around yield class $12-18$, reflecting the relatively poor sites available for planting in the past.

Another potential problem with the method, but one that can be extended to time series data where only one set of measurements is available, is that a 'snapshot' value may not be truly representative of true overall values. Evidence from stem analysis trees shows that parameter values do not remain constant over the life time of the tree and particularly in the first 40 years are changing rapidly. This may in part be due to inappropriate allocation of $c_{2}$ values but further investigations would be necessary to confirm this.

The function is also age sensitive. If the wrong age is used then $c_{1}$ can be altered by over $8 \%$ per year of difference for younger trees. This is less of a problem at older ages and suggests that it may be more appropriate to sample older stands because of this. The age attributed to a tree is important and a consistent approach is necessary. CLG10 was assumed to be 36 years old from the planting date given but most of the stem analysis trees yielded ages of only 35 years.

### 5.2 Stem analysis trees

### 5.2.1 Parameter estimation.

Of the three parameter estimation techniques the grid search produced the least satisfactory results. In addition the routine was very slow and could take several hours to run especially for older trees. Simulated annealing was far quicker and, because it used the same optimisation criteria, gave very similar values to non linear regression. With this technique it is necessary to be aware that the starting conditions can influence the results and some testing of the method was necessary to establish the appropriate settings. In particular if the initial temperature is too low or the cooling rate too rapid the optimum solution might not be found. On the other hand if the initial temperature is too high, the cooling rate too slow and the number of iterations large the routine takes a long time to run with no great increase in efficiency. For this exercise a start temperature of 1,000 and cooling rate of 0.99 and 10,000 iterations were suitable in most cases. It is easy to modify the routine if necessary, however this was generally only necessary when extreme parameter values were computed. These cases tended to highlight problems in the data such as erratic patterns or very steep or shallow relative increment curves. For general purposes it is possible to restrict the search space of the simulated annealing routine to $c_{1}$ values between 0.1 and 1.0 and $c_{2}$ between 0.5 and 5.0. Simulated annealing provided excellent starting values for the non linear regression routine.

### 5.2.2 Parameter values

The range of estimated parameter values shown in Figs. 4.22 and 4.23 is restricted if the few extreme values are discounted. The majority of trees have values between 0.15 and 0.35 and these could be taken as initial indicators of upper and lower potential values. Values outside these ranges point to possible problems with the data or special conditions affecting growth. This is shown with the very low $c_{1}$ value given to GWY4-3 which therefore appears to be growing extremely quickly. On the other hand some very large trees that have grown quickly have high $c_{1}$ values, CLG10-4 being an example.

With only two parameters the model appears to be able to reflect general growth patterns with some degree of confidence that would be appropriate in a single tree model. At a more detailed level wider discrepancies can be seen and in particular the
two older trees show large bias at mid stages of their growth. Early erratic growth may be able to explain some of this and then possibly changes in growth pattern as trees reach canopy closure from age 15 onwards. The models of trees in CLG10, which is the youngest site, present the closest fit, all other sites showing different degrees and patterns of bias at various stages of growth. It may be that there is a general case for applying at least two sets of parameters to trees of older age as demonstrated with tree ATW1-1947. By splitting the data set different options can be investigated.

It is interesting to note that analysis of 5 yr and 10 yr interval data gave very similar parameters to those based on annual intervals for tree ATW1-1947. Bias was in fact slightly more for 5 yr intervals rather than 10 year data and when the latter's parameters were applied to an annual model bias was slightly improved. However, the similarity in parameter values does suggest that long term inventory data of individual trees can be used to produce appropriate models.

The investigations into appropriate values of $c_{3}$ suggest that in terms of model fit a value of 0.4 , as suggested in the original model, is suitable for British conditions. Values much higher than this tend to raise $c_{1}$ values which may in turn lead to apparent early slowing of growth in trees that are not showing this.

Extrapolation of the models indicates the influence $c_{1}$ has on the growth potential of the tree and it is possible to predict volume many years into the future. However there is a great deal of uncertainty attached to this as trends in bias at the end of the data set indicate. More work is required on the growth patterns of trees in older age before confident predictions can be made.

### 5.3 Combined values

The lack of correspondence between aggregated stand and rapid method $c_{1}$ values is disappointing but perhaps reflects part of the difficulty with the snapshot approach as opposed to a value reflecting a dynamic system. There is however some evidence that there is a close relationship between rapid method $c_{1}$ values and stem analysis values when site specific $c_{2}$ values are applied to the former. When analysed together the combined values of $c_{1}$ were in the range 0.13 and 0.37 , emphasising the findings from individual stem analysis trees. The combined $c_{2}$ values also have a conservative range, and extreme values are associated with sites that were of low yield class and in check.

The regression of combined $c_{1}$ values with yield class suggests that there might indeed be a relationship between stand $c_{1}$ and site productivity. If two sites are omitted from the regression an improved $\mathrm{r}^{2}$ value of 0.7792 is achieved (Fig. 5.2). However great care must be used in interpreting this as the data set is small and the remaining site with yield class 6 and CLG10 with yield class 30 are rather isolated from the rest of the data.


Figure 5.2 Relationship between combined values of $c_{1}$ and yield class before and after removal of two poor sites

If this relationship can be verified it confirms the apparent contradiction that whilst more productive sites have higher $c_{1}$ values than less productive ones, within any given site the larger trees have smaller $c_{1}$ values. Within a site competition and other factors force smaller trees to grow more slowly resulting in them having larger $c_{1}$ values. Between sites productive potential is the driving force and the model parameters reflect the way the stand reaches that potential. A high $c_{1}$ value is associated with early culmination, a feature of high yielding sites. So a tree may be growing at a faster relative rate than one on a nearby site but be much smaller because its potential and absolute growth rate remain small.

### 5.4 Relationship between $c_{1}$ value and environmental variables

The relationships with individual environmental variables are ambiguous at best. For example it is expected that $c_{1}$ should be positively correlated with temperature but this cannot be shown conclusively. There are however weak negative trends with elevation and windiness and positive correlations with SMR and SNR which might be more appropriate. The small number of sites and uncertainty in the establishment of an appropriate measure of $c_{1}$ presumably account for the absence of clearer trends. Site CLG10 frequently has a strong influence on the regressions but nearly always appears as an outlier and more data for sites of yield classes 20 to 30 are required. As has previously been pointed out it was also difficult to find lower yield class sites that were growing uniformly both in time and space. It may be necessary to look outside Wales to adequately sample the range of site types found in Britain.

The results of multiple regression are much more promising and suggest a much stronger relationship between $c_{1}$ and site factors. Careful interpretation of the regressions is advised as different factors appear to influence different measures of $c_{1}$. Elevation is frequently a strong influence which confirms findings of many other studies on site factors and Sitka spruce in Britain (Worrel and Malcolm, 1990a, b; Proe et al., 1996; Bateman and Lovett, 1998). Moisture deficit seems to have a stronger influence than accumulated temperature, with which it is highly correlated, in many models. This may be because it incorporates precipitation as well as temperature in its value. The easting component suggests that there is possibly a weak association with continentality but this cannot be proven with so few data. When $c_{2}$ of the combined methods is regressed against site factors the relationship is not as strong but similar caveats regarding sample size and lack of data need to be taken into consideration. Moisture deficit and age also have a relatively strong influence on the value of $c_{2}$. This may reflect the influence that $c_{2}$ has in the early stages of development trees. Also the degree of wetness may play an important role in modifying early tree growth. As a site dries and trees become better established growth rates may change.

Although the regression improves when $c_{2}$ is variable the number of data points is smaller. There is, however, a demonstrable link between site factors, and moisture deficit again has a stronger influence than accumulated temperature. It is possible to construct a model with moisture deficit, windiness, soil moisture regime and soil nutrient regime with an $\mathrm{r}^{2}$ value of greater than 0.8 .

### 5.5 Conclusions and suggestions for further work

The rapid method is an appropriate choice for collecting increment data for growth modelling if a large number of sites are required to be sampled quickly.

A general pattern of $c_{1}$ and $c_{2}$ variation within and between stands has been established and values of $c_{1}$ between 0.15 and 0.35 are adequate to model both trees and stands of Sitka spruce in Britain. Corresponding values of $c_{2}$ are 0.5 to 3.5 but there is no clear relationship between $c_{1}$ and $c_{2}$ and a simple classification of $c_{1} / c_{2}$ combinations may be more appropriate until more detailed work can be carried out. The use of just two parameters in the model is sufficient to give it a great deal of flexibility.

A number of different estimates of site $c_{1}$ have been tested. A suitable sample of larger trees may be sufficient to establish individual tree potential. The effect of competition has not been investigated but if the largest trees within a stand are also subject to competition the true potential of a site may only be found in open grown trees.

An apparently strong relationship between site specific $c_{1}$ and combined environmental factors is evident. It is recommended that this relationship is investigated further.

It will be important in future investigations to increase the number of, and ensure a wider geographical spread of, sample sites beyond north and mid Wales. Sites representative of conditions found throughout Britain should be sampled and the full range of known yield classes taken into account. Sites with naturally low productivity (i.e. where such low productivity is not due to check and would not be improved by site amelioration) and with moderate to high yield classes need to be included. It is also
important to ensure that environmental variables are adequately sampled across the range of values at which they occur, for example ensuring that drier values of soil moisture regime and richer values of soil nutrient regime are included. If possible account should be taken of genetic variation of the trees themselves. The sample plot system established by Forest Research would prove an ideal starting point for this work.

Specific areas of further work are listed below.

1. The results of this investigation with respect to the range of parameter values, and their relationship with site index, of both individual trees and stands need to be confirmed.
2. Detailed investigation should be carried out into the physiological relationship between parameter values and tree growth.
3. In particular understanding of early growth stages, when form factors are changing rapidly, and the relationship between growth and parameter values and between $c_{1}$ and $c_{2}$, themselves needs to be improved.
4. In addition a greater number of trees and stands, older than 60 years of age, should be assessed to investigate whether the estimation of $c_{1}$ can be improved as both $c_{2}$ and $c_{3}$ lose their influence.
5. Sample plot data should be used to elaborate a preliminary stand growth model based on the multiplier approach. Sensitivity analysis should be carried out to test the flexibility of the model and its ability to predict growth under differing management and environmental conditions.
6. Further work is required to confirm individual tree potential within a stand, on any given site type. The rapid method approach could be used and only larger trees from a stand need be sampled. Stand potential could also be compared to that of open grown trees on the same site types.
7. In order to provide flexibility for modelling mixed stands the effect of both competition and micro-site variation within stands still requires further investigation. A potential modifier approach could then be used to model individual trees within a stand.
8. Continued monitoring of the Tyfiant Coed research plots will continue to provide important data for this work and could be supplemented by the assessment of fully enumerated temporary plots using the rapid method sampling approach to provide increment data.
9. Further refinement of the rapid method and investigations into its practical usefulness, for example in assessing volume and volume increment on sample plots would be beneficial.
10. The modelling of height and diameter through the use of the allometric coefficient and form factors also requires further work.
11. Form factor functions could be developed using the stem analysis data.
12. The relationship between model parameters, including the allometric coefficient, and environmental variables requires more detailed investigation. More advanced statistical techniques than simple linear models could usefully be applied to the current data set and will be necessary for a larger study.
13. As a priority a more detailed and systematic investigation into the response of model parameters to individual environmental variables and the establishment of a robust set of dose response functions should be carried out.
14. Different approaches to estimating site specific parameters from these dose response functions should be tested (e.g. Pretzsch and Kahn, 1995; Pyatt et al., 2001).
15. Consideration should be given to the specific nature of the site variables used in the model. Measures which best explain variability in model parameters whilst at the same time are readily available or easily measured should be used.
16. Stem analysis data should be analysed in conjunction with historical meteorological data to carry out detailed investigations into temporal relationships between tree growth and environmental factors. This could lead to valuable insights into the reaction of individual trees and stands to impending climate change. Stem analysis work could also be extended to include trees from EU level 1 plots where there has been continuous monitoring of soil chemistry.
17. The modelling approach should be extended to include tree species, other than Sitka spruce, that are of interest to British foresters.

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## APPENDICES

## Appendix 1 Distribution of rapid method $c_{1}$ values for individual sites.



CLG8


CLG9


CLG10

## Appendix 1 continued



CLG11


CLG12


GWY3

Appendix 1 continued


GWY4


GWY5


## GWY6

Appendix 1 cont


GWY7


GWY8


## Appendix 1 cont



PEN1


UPM1


UPM2

## Appendix 1 continued



BAD1


BAD2

Appendix 2 Values of $c_{1}$ and $c_{2}$ estimated from simulated annealing and non linear regression

| Forest | site | $\begin{gathered} \text { tree } \\ \text { number } \end{gathered}$ | simulated annealing |  |  |  | non linear regression |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | C1 | C2 | m | SS(v) | C1 | C2 | m | SS(v) | SS(h) | SE(v) |
| CLG | 8 | 1 | 0.211038 | 1.51987 | 2.6898 | 0.01543 | 0.210987 | 1.521168 | 2.689478 | 0.01543 | 0.005223 | 0.023066 |
| CLG | 8 | 4 | 0.235295 | 0.500048 | 2.0791 | 0.02414 | 1.193808 | 0.071497 | 2.11218 | 0.014883 | 0.00299 | 0.026622 |
| CLG | 8 | 7 | 0.205525 | 2.678126 | 2.761 | 0.006003 | 0.205525 | 2.678126 | 2.761002 | 0.006003 | 0.004761 | 0.014387 |
| CLG | 9 | 1 | 0.193491 | 3.311182 | 2.5836 | 0.004532 | 0.19349 | 3.310696 | 2.583674 | 0.004532 | 0.001228 | 0.012722 |
| CLG | 9 | 4 | 0.244483 | 1.885042 | 2.4911 | 0.009804 | 0.244438 | 1.886238 | 2.49088 | 0.009804 | 0.002134 | 0.018712 |
| CLG | 9 | 13 | 0.499983 | 0.500843 | 2.0959 | 0.025744 | 1.841287 | 0.117175 | 2.129716 | 0.019494 | 0.009135 | 0.026386 |
| CLG | 10 | 1 | 0.251823 | 2.360101 | 2.4543 | 0.004999 | 0.251742 | 2.361743 | 2.454242 | 0.004999 | 0.005529 | 0.013866 |
| CLG | 10 | 2 | 0.430782 | 0.830171 | 2.3114 | 0.006233 | 0.436591 | 0.813962 | 2.314082 | 0.006231 | 0.002612 | 0.015481 |
| CLG | 10 | 3 | 0.25694 | 1.867845 | 2.7635 | 0.002384 | 0.257048 | 1.865925 | 2.763766 | 0.002384 | 0.002579 | 0.009577 |
| CLG | 10 | 4 | 0.437038 | 0.682484 | 2.8325 | 0.002882 | 0.424912 | 0.708697 | 2.82793 | 0.002877 | 0.005714 | 0.01052 |
| CLG | 10 | 8 | 0.409879 | 0.978849 | 2.6113 | 0.008777 | 0.412227 | 0.970501 | 2.612646 | 0.008777 | 0.003385 | 0.018373 |
| CLG | 10 | 15 | 0.347607 | 1.564659 | 2.6876 | 0.003063 | 0.34725 | 1.567666 | 2.687239 | 0.003063 | 0.00264 | 0.010854 |
| CLG | 11 | 1 | 0.149038 | 4.644071 | 2.4038 | 0.039622 | 0.149046 | 4.64265 | 2.403851 | 0.039622 | 0.00447 | 0.034651 |
| CLG | 11 | 3 | 0.188363 | 1.405001 | 2.6577 | 0.021248 | 0.188463 | 1.403664 | 2.657702 | 0.021248 | 0.007776 | 0.024999 |
| CLG | 11 | 5 | 0.370331 | 0.500038 | 2.5174 | 0.012809 | 0.566969 | 0.29231 | 2.564318 | 0.011838 | 0.011828 | 0.01894 |
| CLG | 11 | 11 | 0.178616 | 2.016789 | 2.6218 | 0.014677 | 0.178582 | 2.01785 | 2.621743 | 0.014677 | 0.003055 | 0.020777 |
| CLG | 11 | 12 | 0.177982 | 0.918992 | 2.7361 | 0.00768 | 0.178624 | 0.913664 | 2.736518 | 0.007679 | 0.006212 | 0.015491 |
| CLG | 12 | 1 | 0.136799 | 1.752191 | 2.6674 | 0.019474 | 0.136983 | 1.747366 | 2.667522 | 0.019474 | 0.013381 | 0.025064 |
| CLG | 12 | 2 | 0.106234 | 2.919253 | 2.9309 | 0.120251 | 0.112652 | 3.741283 | 2.748531 | 0.117499 | 0.019522 | 0.060596 |
| CLG | 12 | 3 | 0.255881 | 1.28414 | 2.5614 | 0.165082 |  |  |  |  |  |  |

## Appendix 2 continued

Values of $c_{1}$ and $c_{2}$ estimated from simulated annealing and non linear regression

| Forest | site | $\begin{gathered} \text { tree } \\ \text { number } \end{gathered}$ | simulated annealing |  |  |  | non linear regression |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | C1 | C2 | m | SS(v) | C1 | C2 | m | SS(v) | SS(h) | SE(v) |
| CLG | 12 | 4 | 0.147077 | 4.999954 | 2.5363 | 0.067638 |  |  |  |  |  |  |
| CLG | 12 | 5 | 0.218891 | 2.289696 | 2.592 | 0.011325 | 0.218906 | 2.289402 | 2.591999 | 0.011325 | 0.004928 | 0.018525 |
| CLG | 12 | 6 | 0.124873 | 2.433518 | 2.6309 | 0.031518 | 0.124877 | 2.432975 | 2.631 | 0.031518 | 0.004259 | 0.031384 |
| CLG | 12 | 7 | 0.114106 | 3.072588 | 2.4481 | 0.194906 |  |  |  |  |  |  |
| CLG | 12 | 8 | 0.221821 | 2.081691 | 2.8724 | 0.042762 | 0.22193 | 2.079731 | 2.872401 | 0.042762 | 0.011864 | 0.036555 |
| CLG | 12 | 9 | 0.112409 | 1.451732 | 2.5569 | 0.056932 | 0.11223 | 1.457363 | 2.556745 | 0.056932 | 0.015773 | 0.042855 |
| CLG | 12 | 10 | 0.171896 | 2.671913 | 2.41 | 0.036455 | 0.171894 | 2.672104 | 2.410001 | 0.036455 | 0.004431 | 0.034293 |
| CLG | 12 | 11 | 0.145138 | 1.751888 | 2.6367 | 0.04232 | 0.145042 | 1.754268 | 2.636698 | 0.04232 | 0.026495 | 0.036366 |
| CLG | 12 | 12 | 0.222346 | 1.087109 | 2.4776 | 0.024018 | 0.222544 | 1.085653 | 2.4776 | 0.024018 | 0.008412 | 0.026978 |
| CLG | 12 | 13 | 0.10187 | 4.999931 | 2.6895 | 0.070494 |  |  |  |  |  |  |
| CLG | 12 | 14 | 0.123753 | 4.999912 | 2.7066 | 0.028727 |  |  |  |  |  |  |
| CLG | 12 | 15 | 0.155947 | 3.70583 | 2.6191 | 0.017827 | 0.155953 | 3.705636 | 2.619041 | 0.017827 | 0.010776 | 0.023981 |
| GFS | 1 | 6 | 0.330147 | 1.31562 | 2.2643 | 0.017723 | 0.330217 | 1.314885 | 2.264432 | 0.017723 | 0.001684 | 0.022502 |
| GFS | 1 | 7 | 0.20098 | 3.06262 | 2.8044 | 0.006285 | 0.200969 | 3.063284 | 2.8044 | 0.006285 | 0.001626 | 0.014015 |
| GFS | 1 | 12 | 0.252807 | 4.999418 | 2.6248 | 0.006063 | 0.251021 | 5.240067 | 2.617757 | 0.006046 | 0.000353 | 0.013966 |
| GWY | 3 | 16 | 0.297021 | 0.569773 | 2.9015 | 0.011474 | 0.313826 | 0.52846 | 2.90922 | 0.011456 | 0.002868 | 0.020598 |
| GWY | 4 | 3 | 0.100014 | 0.630815 | 2.6942 | 0.318421 |  |  |  |  |  |  |
| GWY | 4 | 5 | 0.287738 | 0.500086 | 2.5442 | 0.069408 | 1.558598 | 0.073417 | 2.619807 | 0.055348 | 0.00986 | 0.042953 |
| GWY | 4 | 10 | 0.115285 | 4.999954 | 2.3314 | 0.144767 |  |  |  |  |  |  |
| GWY | 5 | 9 | 0.191222 | 1.166284 | 2.6733 | 0.022482 | 0.190906 | 1.169272 | 2.673298 | 0.022482 | 0.011174 | 0.027843 |

## Appendix 2 continued

Values of $c_{1}$ and $c_{2}$ estimated from simulated annealing and non linear regression

| Forest | site | $\begin{gathered} \text { tree } \\ \text { number } \end{gathered}$ | simulated annealing |  |  |  | non linear regression |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | C1 | C2 | m | SS(v) | C1 | C2 | m | SS(v) | SS(h) | SE(v) |
| GWY | 6 | 1 | 0.132601 | 4.999954 | 2.7779 | 0.042933 |  |  |  |  |  |  |
| GWY | 6 | 10 | 0.257428 | 42.79635 | 2.4508 | 0.009062 | 0.257428 | 42.79737 | 2.450801 | 0.009062 | 0.008297 | 0.01738 |
| GWY | 6 | 11 | 0.174956 | 4.999954 | 2.4857 | 0.098335 |  |  |  |  |  |  |
| GWY | 6 | 13 | 0.238323 | 18.71516 | 2.1356 | 0.066453 | 0.238333 | 18.71324 | 2.135599 | 0.066453 | 0.023099 | 0.047065 |
| GWY | 7 | 2 | 0.318309 | 1.469086 | 2.3176 | 0.003053 | 0.317744 | 1.473356 | 2.317405 | 0.003053 | 0.003442 | 0.010442 |
| GWY | 7 | 4 | 0.267318 | 1.867145 | 2.9915 | 0.003452 | 0.267318 | 1.867143 | 2.991499 | 0.003452 | 0.008851 | 0.011103 |
| GWY | 7 | 6 | 0.159974 | 4.999931 | 2.8346 | 0.012158 |  |  |  |  |  |  |
| GWY | 7 | 13 | 0.499983 | 1.382404 | 1.9399 | 0.005555 | 0.514142 | 1.325995 | 1.942892 | 0.005542 | 0.009077 | 0.013823 |
| GWY | 8 | 1 | 0.216958 | 4.999931 | 2.8473 | 0.007154 | 0.204408 | 8.706551 | 2.75617 | 0.005806 | 0.002391 | 0.014149 |
| GWY | 8 | 2 | 0.185675 | 4.999912 | 2.9999 | 0.036965 |  |  |  |  |  |  |
| GWY | 8 | 3 | 0.268902 | 4.999954 | 2.4274 | 0.020718 | 0.246719 | 17.418 | 2.339046 | 0.016479 | 0.009352 | 0.023437 |
| GWY | 8 | 4 | 0.166594 | 4.999912 | 2.6429 | 0.065127 |  |  |  |  |  |  |
| GWY | 8 | 53 | 0.289156 | 4.999418 | 2.9145 | 0.017774 | 0.279909 | 6.125909 | 2.872469 | 0.017369 | 0.002621 | 0.024907 |
| GWY | 8 | 525 | 0.180216 | 4.999418 | 2.9808 | 0.029142 |  |  |  |  |  |  |
| GWY | 8 | 6 | 0.146062 | 4.999418 | 2.9115 | 0.026542 |  |  |  |  |  |  |
| GWY | 8 | 7 | 0.111658 | 4.999418 | 2.408 | 0.087625 |  |  |  |  |  |  |
| GWY | 8 | 84 | 0.180677 | 4.999931 | 2.6955 | 0.124467 |  |  |  |  |  |  |
| GWY | 8 | 828 | 0.460238 | 1.01737 | 2.2758 | 0.221945 |  |  |  |  |  |  |
| GWY | 8 | 99 | 0.245282 | 2.189759 | 2.7026 | 0.015294 | 0.245328 | 2.188888 | 2.702603 | 0.015294 | 0.001792 | 0.022579 |

## Appendix 2 continued

Values of $c_{1}$ and $c_{2}$ estimated from simulated annealing and non linear regression

| Forest | site | $\begin{gathered} \text { tree } \\ \text { number } \end{gathered}$ | simulated annealing |  |  |  | non linear regression |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | C1 | C2 | m | SS(v) | C1 | C2 | m | SS(v) | SS(h) | SE(v) |
| GWY | 8 | 919 | 0.22556 | 4.999954 | 2.9999 | 0.011003 | 0.211985 | 9.308345 | 2.981724 | 0.010291 | 0.003741 | 0.018521 |
| GWY | 8 | 10 | 0.183877 | 4.999954 | 2.335 | 0.048093 |  |  |  |  |  |  |
| GWY | 8 | 11 | 0.233365 | 2.785658 | 2.6898 | 0.020577 | 0.233446 | 2.784188 | 2.689656 | 0.020577 | 0.009901 | 0.02619 |
| GWY | 8 | 12 | 0.160371 | 4.999954 | 2.8652 | 0.014645 |  |  |  |  |  |  |
| PEN | 1 | 3 | 0.230202 | 3.844532 | 2.6663 | 0.007183 | 0.230199 | 3.844518 | 2.666299 | 0.007183 | 0.003311 | 0.013933 |
| PEN | 1 | 5 | 0.274116 | 1.87613 | 2.3703 | 0.007101 | 0.274155 | 1.875824 | 2.37022 | 0.007101 | 0.003234 | 0.01367 |
| PEN | 1 | 7 | 0.287053 | 0.571947 | 2.7975 | 0.036915 | 0.291092 | 0.56007 | 2.800574 | 0.036912 | 0.005418 | 0.031167 |
| PEN | 1 | 8 | 0.449691 | 0.605368 | 2.1391 | 0.034566 | 0.457776 | 0.589813 | 2.142798 | 0.034562 | 0.00792 | 0.030159 |
| PEN | 1 | 9 | 0.230489 | 2.129074 | 2.3047 | 0.03513 | 0.230497 | 2.128903 | 2.304702 | 0.03513 | 0.011294 | 0.030405 |
| UPM | 1 | 1 | 0.100014 | 2.977602 | 2.449 | 0.055824 |  |  |  |  |  |  |
| UPM | 1 | 2 | 0.119234 | 4.999931 | 2.4542 | 0.042164 |  |  |  |  |  |  |
| UPM | 1 | 6 | 0.218516 | 0.802975 | 2.4367 | 0.023964 | 0.2202 | 0.793618 | 2.437622 | 0.023963 | 0.013836 | 0.028746 |
| UPM | 1 | 15 | 0.155484 | 1.247793 | 2.8002 | 0.011376 | 0.154808 | 1.257403 | 2.799793 | 0.011376 | 0.005764 | 0.020156 |
| UPM | 2 | 2 | 0.196186 | 4.999418 | 2.6538 | 0.010343 | 0.195292 | 5.200539 | 2.64773 | 0.010328 | 0.002226 | 0.016486 |
| UPM | 2 | 6 | 0.308512 | 1.087976 | 2.2732 | 0.043836 | 0.309417 | 1.081948 | 2.274138 | 0.043836 | 0.033685 | 0.03539 |
| UPM | 2 | 7 | 0.273927 | 1.266257 | 2.4753 | 0.028614 | 0.274099 | 1.264563 | 2.475636 | 0.028614 | 0.004913 | 0.027809 |
| UPM | 2 | 10 | 0.155054 | 4.999931 | 2.3778 | 0.050988 |  |  |  |  |  |  |
| BAD | 1 | 4 | 0.177938 | 1.072006 | 2.6555 | 0.016244 | 0.176183 | 1.090282 | 2.653851 | 0.016242 | 0.027007 | 0.024526 |
| BAD | 1 | 6 | 0.261175 | 0.309717 | 2.648 | 0.047217 | 0.614704 | 0.119998 | 2.670593 | 0.04472 | 0.007944 | 0.040698 |
| BAD | 1 | 8 | 0.546117 | 0.491487 | 2 | 0.028653 | 0.626875 | 0.414186 | 1.759723 | 0.028584 | 0.035134 | 0.032537 |
| BAD | 2 | 1 | 0.657761 | 2.106475 | 2.0666 | 0.001703 | 0.657537 | 2.107554 | 2.066525 | 0.001703 | 0.017359 | 0.007799 |
| BAD | 2 | 9 | 0.291098 | 3.288402 | 2.4204 | 0.005151 | 0.29108 | 3.288584 | 2.420493 | 0.005151 | 0.000441 | 0.013563 |
| BAD | 2 | 12 | 0.264209 | 1.906616 | 2.674 | 0.005281 | 0.264168 | 1.90718 | 2.673998 | 0.005281 | 0.002149 | 0.013986 |

## Appendix 3 Individual tree models for stem analysis trees by site



CLG8


CLG9


CLG10


CLG11




GFS1


GWY4


GWY6


GWY7


GWY8


PEN1


UPM1


UPM2

