DOCTOR OF PHILOSOPHY

Measuring and modelling sitka spruce (Picea sitchensis (bong.) carriere) and birch (Betula spp.) crowns, with special reference to terrestrial photogrammetry

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Measuring and Modelling Sitka Spruce (*Picea sitchensis* (Bong.) Carrière) and Birch (*Betula* spp.) Crowns, with Special Reference to Terrestrial Photogrammetry

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by

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ABSTRACT

Tree crown dimension and profile (shape) data are often required as inputs to competition indices within single-tree growth and yield models. Crown radius and length were measured for 75 birch (*Betula* spp.) and 154 Sitka spruce (*Picea sitchensis* (Bong.) Carrière) sample trees in permanent sample plots in Wales, and crown shapes of 40 trees were assessed using a "crown window". Crown radius models based on stem diameter at breast height (*dbh*) and parameterised for individual stands perform best. Where a single parameterisation must provide data for all stands, a model incorporating stem dimensions is best for birch, and a model incorporating stem dimensions, local stocking and *dbh* dominance is best for spruce. Crown radius modelling results are poor for heavily suppressed birch. To ensure realistic model behaviour across multiple time steps, a crown length model based on tree height alone is best for both species. The length of the light crown, above the point of maximum crown radius, is roughly two thirds of birch total crown length and three quarters of spruce crown length. Light crown profile models give acceptable results for birch and spruce, but shade crown profile models fail to account for variation in crown shapes, even with spatial variables as inputs, and an alternative model is suggested. Crown window and terrestrial photogrammetry crown profile data for three spruce were compared, using the software PhotoModeler Pro 5 to produce three-dimensional maps of branch tips from photographs. These methods produce comparable profile data for Sitka spruce up to four metres in height. Photogrammetric analyses of birch and larger spruce present considerable difficulties. The crown window can be used more widely, but photogrammetry can potentially yield more data; this is demonstrated by reconstructing spruce branch tips for a previous growing season and examining changes in branch length and crown shape.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS USED IN THE TEXT

α_0	= uniform angle index reference angle (72°)
α_j	= smallest angle between neighbour *j* and next nearest neighbour clockwise
Δh	= height increment (m)
a	= regression coefficient
az	= azimuth of aspect (radians)
A	= crown polygon area (m^2); height angle (°)
A_s	= stand age (years)
A_t	= tree age (years)
b	= regression coefficient
BA	= stand basal area ($m^2\ ha^{-1}$)
$BA_{0.01}$	= basal area of 0.01 ha circular plot ($m^2\ ha^{-1}$)
$BA_{0.02}$	= basal area of 0.02 ha circular plot ($m^2\ ha^{-1}$)
BA_{HA}	= basal area of competitors selected by height angle (m^2)
BAL	= basal area of larger trees ($m^2\ ha^{-1}$)
BAL_{HA}	= basal area of larger competitors selected by height angle (m^2)
c	= regression coefficient
CCF	= crown competition factor
$CCFL$	= crown competition factor of larger trees
CR	= crown ratio
$\overline{CR}$	= stand mean crown ratio
CV	= coefficient of variation
d	= regression coefficient
dbh	= diameter at breast height (cm)
$\overline{dbh}$	= stand mean *dbh* (cm)
D_{base}	= vertical distance from crown base (m)
$Dr_{\max}$	= vertical distance from height of maximum crown radius (m)
D_{tip}	= vertical distance from crown tip (m)
f	= regression coefficient
h	= total height (m)
h_{100}	= stand top height (m)
h_{dom}	= stand dominant height (m)
hcb	= height to crown base (m)
$HDist$	= horizontal distance to nearest neighbour (m)
$HDist_{ij}$	= horizontal distance between subject tree *i* and competitor/neighbour *j* (m)
$Hg_{0.01}$	= Hegyi competition index for 0.01 ha circular plot
$Hg_{0.02}$	= Hegyi competition index for 0.02 ha circular plot
Hg_{HA}	= Hegyi competition index for competitors selected by height angle
Hg_{Rel}	= Hegyi competition index for competitors selected by relascope
i	= subject/reference tree
j	= competitor/neighbour tree

L	= light or shade crown length (m)
L_{light}	= light crown length (m)
L_{shade}	= shade crown length (m)
L_{total}	= total crown length (m)
M	= species mingling index
n	= number of neighbours; number of observations; number of vertices
$N_{0.01}$	= stocking of 0.01 ha circular plot (stems ha^{-1})
$N_{0.02}$	= stocking of 0.02 ha circular plot (stems ha^{-1})
N_{HA}	= number of competitors selected by height angle (stems)
PL	= peatland dummy variable (0, mineral soil; 1, peatland)
r	= crown radius (m)
$r_{\max}$	= maximum crown radius (m)
$\bar{r}_{\max}$	= arithmetic mean maximum crown radius (m)
RCD	= relative canopy displacement
sl	= slope (tangent of slope angle, % / 100)
S	= triangular spacing (m)
t	= current time period (years)
$t-1$	= previous time period (years)
U	= dimension dominance index
$Udbh$	= *dbh* dominance index
Uh	= height dominance index
v_j	= structural index variable for neighbour j
W	= uniform angle index
x	= independent variable
x_i	= ith prediction
X_C	= crown polygon centroid X co-ordinate (m)
X_i	= ith crown vertex X co-ordinate (m); ith observation
$\overline{X}$	= mean observation
y	= dependent variable
Y_C	= crown polygon centroid Y co-ordinate (m)
Y_i	= ith crown vertex Y co-ordinate (m)
Z	= elevation (Z co-ordinate) (m)

Sample plot nomenclature

CLG1-3	= Clocaenog permanent sample plots
CLGS	= Clocaenog shelterwood strip
CYB1-3	= Coed y Brenin permanent sample plots
GWY1	= Gwydyr permanent sample plot

Model nomenclature

L1-4	= total crown length models
LL1-4	= light crown length models
P1-4	= crown profile models
R1-7	= maximum crown radius models

Species nomenclature

BI	= birch (*Betula* spp.)
SS	= Sitka spruce (*Picea sitchensis* (Bong.) Carrière)

TREE SPECIES COMMON NAMES USED IN THE TEXT

Scientific names and authorities are taken from the UK National Biodiversity Network (NBN) Gateway website (http://www.searchnbn.net/), except for Maries fir and loblolly pine, taken from the International Plant Names Index (http://www.ipni.org/index.html).

ash	*Fraxinus* spp., *Fraxinus excelsior* L.
beech	*Fagus sylvatica* L.
birch	*Betula* spp.
birch, paper	*Betula papyrifera* Marshall
birch, silver	*Betula pendula* Roth
cedar, western red	*Thuja plicata* Donn ex D. Don
cottonwood	*Populus balsamifera* subsp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw
cypress, hinoki	*Chamaecyparis obtusa* (Siebold and Zucc.) Endl.
fir, amabilis	*Abies amabilis* Dougl. ex Forbes
fir, Douglas	*Pseudotsuga menziesii* (Mirb.) Franco
fir, Maries	*Abies mariesii* Mast.
fir, silver	*Abies alba* Mill.
fir, subalpine	*Abies lasiocarpa* (Hook.) Nutt.
fir, Veitch's silver	*Abies veitchii* Lindl.
hemlock, western	*Tsuga heterophylla* (Raf.) Sarg.
larch	*Larix* spp.
larch, European	*Larix decidua* Mill.
lime	*Tilia* spp.
maple	*Acer* spp.
oak	*Quercus* spp.
oak, pedunculate	*Quercus robur* L.
oak, red	*Quercus rubra* L.
oak, sessile	*Quercus petraea* (Matt.) Liebl.
pine, black	*Pinus nigra* J.F. Arnold
pine, loblolly	*Pinus taeda* L.
pine, lodgepole	*Pinus contorta* Douglas ex Loudon, *Pinus contorta* var. *latifolia* Engelm.
pine, ponderosa	*Pinus ponderosa* Douglas ex Lawson & C. Lawson
pine, radiata	*Pinus radiata* D. Don
pine, Scots	*Pinus sylvestris* L.
pine, stone	*Pinus cembra* L.
poplar	*Populus* spp.
redwood	*Sequoia sempervirens* (D. Don) Endl.
rowan	*Sorbus aucuparia* L.
spruce, Norway	*Picea abies* (L.) H. Karst.
spruce, Sitka	*Picea sitchensis* (Bong.) Carrière
sugi	*Cryptomeria japonica* (L. f.) D. Don
willow	*Salix* spp.

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For my father.

1 INTRODUCTION

1.1 Post-war forestry policy in Wales

The Forestry Commission was formed in 1919 in response to the difficulties of maintaining timber supplies during the First World War, when British forests were unable to supply war-time demands and imports were unreliable. The first "national forest policy" charged the Forestry Commissioners with "the creation in Great Britain and Ireland of reserves of standing timber sufficient to meet the essential requirements of the nation over a limited period of three years in time of war or national emergency" (Forestry Commission, 1921), a goal pursued largely through rapid afforestation with fast-growing, often exotic, coniferous species in uniform blocks. Woodland cover in the United Kingdom has since increased from around 5 % to nearly 12 % (Forestry Commission, 2004a). As the national forest estate has expanded and matured, so too have the policies governing state forestry, culminating in the adoption of the principles of sustainable forest management (Forestry Commission, 2004b). The nation's forests are now expected to provide multiple, sustainable benefits, be they commercial, social or environmental.

Devolution in 1999 transferred control over Welsh forestry policy from Westminster to the National Assembly for Wales. The Assembly responded by consulting widely on a forestry strategy, published in 2001 as *Woodlands for Wales* (Forestry Commission, 2001). The strategy identifies continuous cover forestry (CCF) as a highly desirable alternative to single-aged plantations managed under clear-felling systems, and outlines a commitment "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" and "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, p. 25).

1.2 Continuous cover forestry

Continuous cover forestry is characterised by Mason *et al.* (1999) as "the avoidance of clearfelling of areas much more than two tree heights wide without the retention of some mature trees". This broad approach to forest management encompasses a range of silvicultural systems (Hart, 1995) of which foresters in the United Kingdom have relatively little experience (Mason *et al.*, 1999). Existing yield models (Edwards and Christie, 1981), developed for even-aged monocultures, are unable to provide accurate growth and yield predictions for more complex stands, and a need has been identified for more flexible models to support management decisions (Pommerening and Wenk, 2002).

1.3 The *Tyfiant Coed* project

The *Tyfiant Coed* project was established "to develop a decision support system for continuous cover forestry with Sitka spruce and birch which produces alternative silvicultural scenarios for specific forest stands and delivers accurate forecasts in terms of yield, economics and ecological consequences" (Pommerening, unpubl.), in direct support of the aims of *Woodlands for Wales*. The objectives of the project are as follows:

1. To establish a small number of accurately located experimental and permanent sample plots in stands of Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and birch (*Betula* spp.) in planted and semi-natural forests in the form of growth series.
2. To develop a site-dependent, distance-dependent, single-tree growth model for Sitka spruce and birch, using data from the plots.
3. To validate the model and compare it with other growth and yield models currently used in Britain.

Within the *Tyfiant Coed* growth model, crown dimensions are required at each modelling time step as components of a competition index which will be used to predict stem diameter growth.

1.4 Crown modelling

The crown is vital to the tree as the site of photosynthesis. Crown dimensions are related to foliage surface area and volume, which are in turn related to the scale of the photosynthetic apparatus and its capacity to fuel growth; consequently, a close relationship often exists between crown dimensions and stem dimensions (Oliver and Larson, 1996). This relationship has been exploited by models which use crown size as the basis for competition indices which reduce stem growth from some notional potential value; this is the "potential-modifier" approach described by Gadow and Hui (1999, p. 160). These models rely on the fact that, to a large extent, the size and configuration of tree crowns determine and are determined by the competitive interactions between trees (Oliver and Larson, 1996; Gadow and Hui, 1999). In addition, the crown plays an important part in determining timber quality (Mäkelä and Mäkinen, 2003), tree stability (Cucchi *et al.*, 2005), reproductive capacity (Davies, 2001), below-canopy light environment (Hale, 2004), and habitat quality (Summers and Proctor, 1999), factors which may be important to the modelling process or as outputs in their own right.

1.5 Research questions

Competition indices based on the interaction of tree crowns (Gadow and Hui, 1999) usually require knowledge of crown dimensions such as length and width and, in some cases, the shape, or profile, of the crown (e.g. Pretzsch *et al.*, 2002). In this context, the research questions addressed by the present work are as follows:

1. Which existing crown dimension and profile models give the best predictions for birch and Sitka spruce, in terms of efficiency, bias and precision?
2. Are there relationships between crown dimensions and stand structure, and can spatial variables be used to improve model predictions?
3. Overall, which models are likely to be most suitable for inclusion in the *Tyfiant Coed* growth and yield model?
4. Can terrestrial photogrammetry be employed to gather crown dimension and profile data? If so, are data comparable with those collected using established methods? What is the potential of this method, and what are its limitations?

2 LITERATURE REVIEW

2.1 The tree crown

The crown of a tree may be defined as "the system of its photosynthetic organs together with the nonphotosynthetic organs by which they are physically and physiologically supported, translocating carbohydrates to the stem" (Ottorini *et al.*, 1996). It is of singular importance to the tree as the site of photosynthesis, and its size and form both determine and respond to the tree's competitive interactions with its neighbours; its dimensions are commensurately important in growth and yield modelling as indicators of tree vigour and growth potential and as elements in the quantification of inter-tree competition.

2.1.1 The importance of the crown

At the most fundamental level, tree growth is determined by the scale and efficiency of the photosynthetic apparatus in the crown (Matthews, 1963; Kozlowski, 1971b; Sprinz and Burkhart, 1987; Maguire and Hann, 1989; Kozlowski *et al.*, 1991). Many authors have observed relationships between various measures of crown size (as surrogates for leaf area) and stem dimensions or increment. Smith (1994), for example, found that "the exposed surface area of the crown to sunlight" was a valuable measure for the prediction of annual volume increment in loblolly pine (*Pinus taeda* L.), while Hann and Hanus (2004) found that Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) crown length and width were correlated with total leaf area, "a measure of the tree's potential for producing photosynthate", and that crown ratio (crown length divided by tree height) was useful for predicting height and diameter growth rates. Crown size not only determines the rate of timber production but also timber quality. The vertical extent of the crown in particular affects timber quality by determining stem taper (and therefore grain angle) and the distribution of dead and live branches (and therefore the distribution of dead and live knots) (Maguire *et al.*, 1991; Colin and Houllier, 1992; Briggs, 1996; Mäkelä and Mäkinen, 2003; Fahlvik *et al.*, 2005). The crown influences individual tree stability both by determining stem taper (Oliver and Larson, 1996) and by determining the magnitude of wind loading (Cucchi *et al.*, 2005). Tree reproductive capacity, measured in terms of the quantity and viability of seed produced, tends to be greatest in trees with large crowns (Davies, 2001).

Growth rate, timber quality, individual tree stability and the potential for natural regeneration are all important considerations within continuous cover forestry. Crowns are not only significant individually, however, but also collectively as the forest canopy. Song *et al.* (2004) stated that the canopy is the interface between forest and atmosphere, and that it determines "microhabitats for plants and wildlife..., properties of the forest floor (e.g., sun flecks, throughfall), and even belowground processes such as energy flux, regeneration, decomposition, and respiration... The spatial and temporal properties of these biophysical processes are directly related to horizontal and vertical arrangement of forest canopies and their changes at multiple temporal scales." Understorey light levels are as critical for successful natural regeneration as adequate seed sources (Hale, 2004). Ishii *et al.* (2004) suggested that increasing the structural complexity of forest canopies at both stand and crown levels can increase the biodiversity and productivity of temperate forest ecosystems. The creation of a resource-rich habitat favours a greater range of canopy-dwelling species, while "spatial, physiological, and temporal differentiation" promote greater productivity through complementary resource use. Some species, such as red squirrel (*Sciurus vulgaris* L.) and crossbills (*Loxia* spp.), may preferentially feed in trees with particular crown forms within their habitats (Summers and Proctor, 1999).

2.1.2 Factors acting upon the crown

A number of factors combine to determine the size and shape of crowns. Kozlowski (1971b) stated that the "amount of leaf surface, the distribution of the crown along the stem, and the metabolic activity of leaves, all of which affect cambial growth, are influenced by environmental fluctuations, plant competition, site, management practices, and catastrophic events such as premature defoliation". A factor of particular importance is the availability of light; this is determined primarily by the degree of shading by surrounding crowns in combination with the effects of slope and aspect (Hasenauer and Monserud, 1996). Umeki (1995) and Muth and Bazzaz (2003) showed that trees can respond to heterogeneous forest light environments by altering patterns of allocation and growth. Generally, however, "the crowns of forest-grown trees recede vertically and decrease in growth rate horizontally as competition for light increases" (Sprinz and Burkhart, 1987). Trees respond to thinning "by slowing down upward crown recession" and "increasing crown width and leaf growth" (Kozlowski, 1971b). In addition to indirect interactions through shading, crowns interact directly through physical constriction and the effects of crown collisions (Rudnicki *et al.*, 2003). Cole and Lorimer (1994) suggested that "significant competitive stress on individual trees is induced only by the ring of competitor trees immediately surrounding the subject tree crown". It is the strength of the interactions between the crowns of neighbouring trees, coupled with the correlation between crown size and stem growth, that is the basis for the use of crown variables in competition indices in growth and yield models.

2.1.3 Tree crowns in competition indices

Biging and Wensel (1990) stated that "[g]rowth and yield studies... have employed a paradigm of growth that has two major components: (i) potential growth and (ii) reduction due to competition." This "potential-modifier" approach (Gadow and Hui, 1999) depends on competition indices "to quantify in a simple expression, the effects of neighbouring trees (or other plants) on the growth of an individual in a forest stand" (Vanclay, 1994). A wide range of indices can be used to quantify competition in single-tree distance-dependent growth models (Biging and Dobbertin, 1992; Vanclay, 1994; Gadow and Hui, 1999). While some indices are based on distance-weighted stem size ratios, others consider the ratios of crown dimensions (cross-sectional area, volume or surface area), constriction and shading by neighbouring crowns, or influence zone overlap (often based on the crown radius of open-grown trees). These crown-based indices may require measures of crown width, length and/or shape as inputs (Figs. 2.1 and 2.2).

While tree crown models can be very complex, in some cases incorporating stochastic elements or explicitly modelling crown asymmetry, or even modelling branch architecture (e.g. Biging and Gill, 1997; Cescatti, 1997; Berezovskava *et al.*, 1997), the data requirements of most competition indices can be satisfied by simple, deterministic models (Gadow, 1996), in keeping with the emphasis of the *Tyfiant Coed* growth model on simplicity and parameter parsimony (Pommerening, unpubl.; Pommerening and Wenk, 2002). The simplified crown characteristics shown in Fig. 2.1 assume that the crown is rotationally symmetrical around the stem axis. Total crown length (L_{total}) is derived from tree total height (h) and height to crown base (hcb). The point of maximum crown radius ($r_{\max}$) marks the boundary between the light crown, fully exposed to light from above, and the shade crown, shaded by the foliage of the light crown (Assmann, 1970). The crown profile (Fig. 2.2) is defined by the crown radius (r) at various distances from the crown tip (D_{tip}), the crown base (D_{base}) or the point of maximum crown radius ($Dr_{\max}$).

Ideally, crown dimensions should be predicted from basic model data such as stem diameter at breast height (dbh), tree total height and spatial relationships between neighbours. Hasenauer and Monserud (1996) noted that such models may be based on single measurements of crown dimensions or on two or more measurements in different time periods; while the latter, dynamic approach, yielding information on crown dimension increment, may be preferable in many situations (Maguire and Hann, 1990), the five-year remeasurement interval of the *Tyfiant Coed* plots means that such an approach is beyond the scope of this study, and the models tested here are, necessarily, static.

Fig. 2.1 Gross dimensions of the crown.

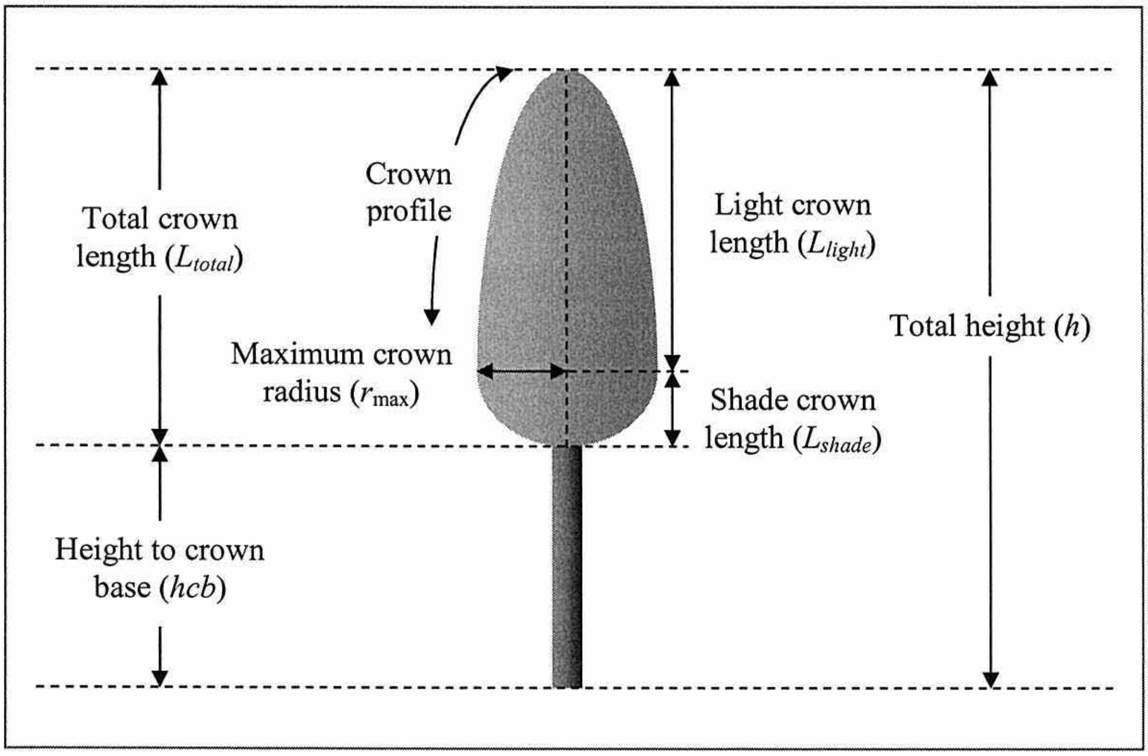
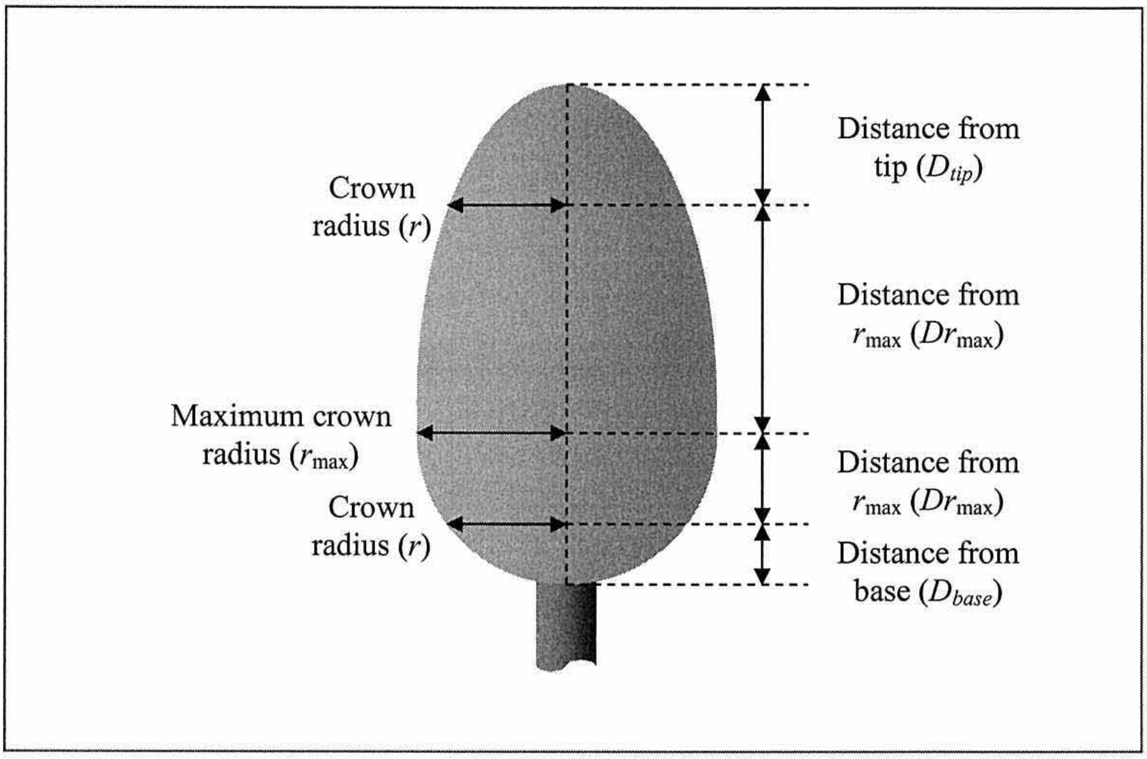


Fig. 2.2 Dimensions of the crown profile.



2.2 Maximum crown radius

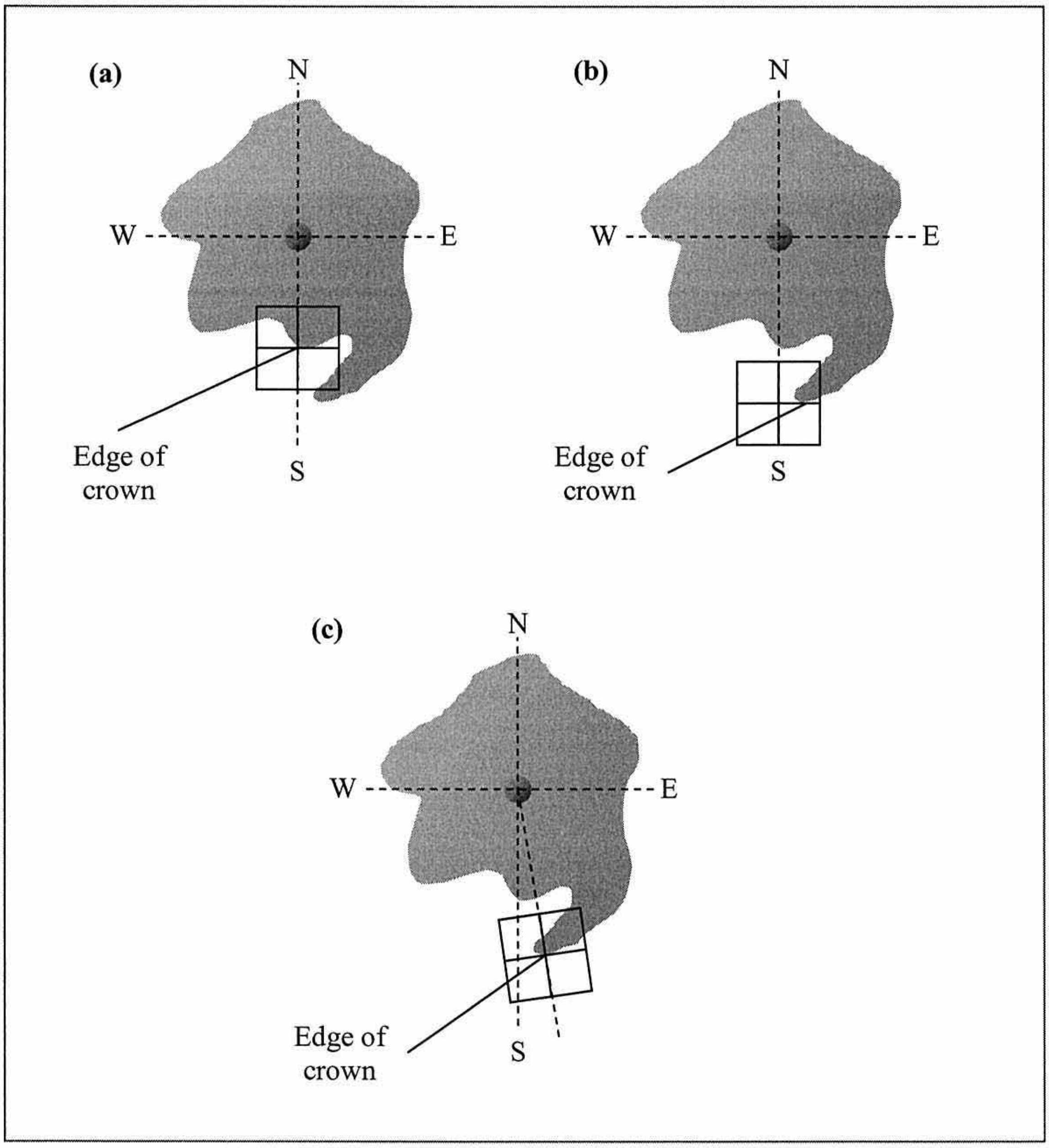
The maximum crown radius determines the crown projection area, that area of ground lying directly below the crown. Crown width and projection area are indirect measures of photosynthetic area (Sprinz and Burkhart, 1987), and because of the dependence of dry matter production on leafiness, crown diameter is often closely correlated with stem diameter (Matthews, 1963). However, Assmann (1970) noted that, in completely closed stands, stem diameter growth continues even though crown expansion is impossible, and that, after thinning, crowns expand more rapidly than stem diameters, confounding the relationship between the two to a degree. Even in stands that maintain full stocking, crown closure can decrease with time as crown collisions and abrasion lead to crown shyness (Oliver and Larson, 1996; Rudnicki *et al.*, 2004). Jack and Long (1991), for example, found that lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) exhibits crown shyness whereas subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) crowns interlock. Overall, the lateral extent and eccentricity of the crown are largely determined by the proximity, size and arrangement of neighbouring trees (Pretzsch, 1992; Laar and Akça, 1997; Muth and Bazzaz, 2003), and as such crown radius gives an indication of the growing space available to a tree. There may be greater scope for variability in crown width and configuration in irregular stands where horizontal and vertical structure are more varied.

2.2.1 Measuring maximum crown radius

Given the nature of the factors acting upon the crown, it is not surprising to find that the crown projection area of a forest-grown tree is never a perfect circle (Laar and Akça, 1997). To account for irregular crown shapes it is common to measure several maximum radii and to derive a mean maximum crown radius; for example, Gill *et al.* (2000) calculated a quadratic mean radius based on two perpendicular radii. In some studies the mean radius is doubled to give a diameter. Hasenauer (1997) derived crown width by "doubling the radius resulting from the quadratic average taken at eight defined directions (N, NE, E, SE, S, SW, W, NW)". While many researchers have taken radius measurements in fixed directions (Minor, 1951; Francis, 1986; Jack and Long, 1991; Cole and Lorimer, 1994; Hasenauer, 1997; Gill *et al.*, 2000; Muth and Bazzaz, 2003; Rudnicki *et al.*, 2003; Rudnicki *et al.*, 2004; Pelt and Nadkarni, 2004), others have deliberately identified the longest radius, sometimes also measuring perpendicular radius (Smith and Bailey, 1964; Sprinz and Burkhart, 1987; Farr *et al.*, 1989; Smith *et al.*, 1992; Canham *et al.*, 1999; Kantola and Mäkelä, 2004; Osada *et al.*, 2004). Canham *et al.* (1999), for example, measured crown radius "by projecting the outermost margin of the crown on the ground, and taking the average of the two longest perpendicular radii", and Smith *et al.* (1992) measured maximum crown diameter and a perpendicular diameter. Tabbush and White (1988), working with open-grown Sitka spruce, measured horizontally from the stem surface to the tips of three branches separated by roughly 120° in the lowest whorl, calculated an average, then doubled the average radius and summed the result with the *dbh* of the tree to give a crown diameter.

A strict definition of the edge of the crown is vital if measurements are to be applied consistently. Fig. 2.3 is adapted from Fig. 3 of Ayhan (1977, p. 69), and shows both correctly (Fig. 2.3(a)) and incorrectly (Fig. 2.3(b) and (c)) identified crown margins. Hamilton (1969) described an alternative approach, defining the crown edge in a given direction as "the limit of the third most extreme branch, i.e. where the crown becomes only two branches 'deep'".

Fig. 2.3 Measuring maximum crown radius. Adapted from Ayhan (1977), this figure shows (a) the correctly located crown margin on a radius measured due south from the tree stem, (b) a branch close to the desired line incorrectly identified as the crown edge, and (c) the measured line shifted from the desired direction so that it crosses the protruding branch.



When attempting to measure crown radius it is important, particularly when working with large trees with high live crowns, to be able to locate accurately the vertical projection of the crown margin onto the ground in order to determine its true horizontal extent. Many authors have described sighting devices designed to improve the accuracy of sighting the crown edge by eye. These devices involve some arrangement of an angled mirror, accurately levelled so that the operator can be sure that he or she is sighting directly upwards from the position of the mirror. Such devices are either hand-held (Buell, 1936; Hetherington, 1967a[1]; Hamilton, 1969; Shepperd, 1973; Ayhan, 1977; Rudnicki *et al.*, 2004) or mounted on a vertical pole (Holdsworth *et al.*, 1936; Amberger *et al.*, 1990). The device described by Turnock and Ives (1957) is unique in that it is mounted on a horizontal pole driven into the tree stem. Once the position of the crown edge in the desired direction has been established using one of these various sighting devices, the radius is simply measured with a tape (or by reading the radius directly from the horizontal pole of the device of Turnock and Ives (1957)).

An alternative to vertically sighting the margins of the crown is to view the tree horizontally from a distance. Devices designed to be used in this way rely on the principle of the similarity of triangles, with a known or fixed distance between the observer's eye and a horizontal measuring piece, and a known or fixed distance to the tree stem (Nash, 1948[2]; Brewer *et al.*, 1959; Hussein *et al.*, 2000). Both Nash (1948) and Brewer *et al.* (1959) corrected for the effect of a difference in height between the observer's eye and the point of maximum crown width on the actual distance to the tree compared with the measured, horizontal distance; Brewer *et al.* (1959) reduced the horizontal distance from observer to tree according to the height difference, while in the device used by Nash (1948) the distance between the observer's eye and the measuring piece can be accurately adjusted. The "crown window" described by Hussein *et al.* (2000) differs from the other devices in that it is used to yield crown width measurements at several heights simultaneously.

Other instruments, such as the "Moosehorn"[3] described by Robinson (1947) and Garrison (1949), do not measure horizontal crown dimensions directly, but instead provide estimates of stand crown cover. Remote sensing, through aerial photography or lidar (light detection and ranging; Evans *et al.*, 2006), has been employed as a means of assessing forest canopies. Several authors (e.g. Minor, 1951; Bonnor, 1964; Zagalikis *et al.*, 2005) have explored relationships between crown dimensions derived from aerial

[1] Ayhan (1977) noted the limitations of the device proposed by Hetherington, whose mirror is only levelled in one horizontal plane.
[2] Vezina (1962) stated that the Nash scale "proved to be somewhat inaccurate, particularly with small trees".
[3] "Because the instrument is similar in shape to a calling device used by big game hunters to attract moose, it was called a "moosehorn"" (Garrison, 1949).

photography and economically important tree attributes such as *dbh* or volume to avoid the need for lengthy ground surveys of stands. Aerial photogrammetry is discussed further in section 2.4.2.

2.2.2 *Modelling maximum crown radius*

It will be appreciated from the preceding section that the measurement of crown radius in the field is a laborious and time-consuming task, seldom undertaken alongside routine forest inventory measurements. Ideally it should be possible to predict values based on some other, routinely measured tree characteristic. Of the various models presented below, some were developed for use in forest stands while others (e.g. Farr *et al.*, 1989; Smith *et al.*, 1992) were intended to predict the maximum crown radius of open-grown trees. The crown width of open-grown trees is often taken to be the maximum potential crown width achievable, and comparisons between such potential values and the actual areas occupied by trees in forest stands have been used as the basis for crowding or competition indices, most famously the "Crown Competition Factor" (*CCF*) of Krajicek *et al.* (1961). Note that some authors calculated crown radius while others calculated crown diameter. The formats of all of their equations have been standardised below to give radius and to use the same coefficient labels; clearly, there will be a difference in the values of coefficients used to predict radius and those used to predict diameter.

Hetherington (1967b) suggested that there is a simple linear relationship between stem and crown diameters in Sitka spruce in Wales. Linear relationships were also found for various broadleaf and conifer species by Minor (1951), Krajicek *et al.* (1961), Vezina (1962, 1963), Curtis and Reukema (1970), Jereb (1972), Francis (1986), Rollinson (1988), Tabbush and White (1988), Smith *et al.* (1992), Nagel (1999), Gill *et al.* (2000), Gilmore (2001) and Rautiainen and Stenberg (2005).

(2.1) $$r_{max} = a + b \cdot dbh$$

where r_{max} = maximum crown radius (m)
dbh = diameter at breast height (cm)
a, b = regression coefficients

Canham *et al.* (1999) found that the intercepts of linear regressions with *dbh* were generally not significantly different from zero in cedar-hemlock forests. Farr *et al.* (1989), on the other hand, added a third regression coefficient to their equations for open-grown Sitka spruce and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.):

(2.2) $$r_{\max} = a + b \cdot dbh^{c}$$

where a, b, c = regression coefficients

Smith *et al.* (1992) and Gill *et al.* (2000) added a quadratic term to the simple linear model:

(2.3) $$r_{\max} = a + b \cdot dbh + c \cdot dbh^{2}$$

Gill *et al.* (2000) also suggested functions in the following forms:

(2.4) $$r_{\max} = a + b \cdot dbh + c \cdot BA$$

(2.5) $$r_{\max} = a + b \cdot dbh + c \cdot hcb$$

(2.6) $$r_{\max} = a + b \cdot dbh + c \cdot Z$$

where BA = stand basal area ($m^2 \ ha^{-1}$)
hcb = height to crown base (m)
Z = elevation (m)

In addition, Gill *et al.* (2000) investigated a number of functions incorporating a dummy variable to represent grouped crown classes. Despite having tested a wide range of models for conifers including Douglas fir, lodgepole pine (*Pinus contorta* Douglas ex Loudon), ponderosa pine (*P. ponderosa* Douglas ex P. & C. Lawson) and redwood (*Sequoia sempervirens* (D. Don) Endl.), the authors found that the linear model based on *dbh* alone gave adequate predictions of crown radius.

Gilmore (2001) considered linear relationships with variables other than *dbh*:

(2.7) $$r_{\max} = a + b \cdot h$$

(2.8) $$r_{\max} = a + b \cdot L_{total}$$

where h = total height (m)
L_{total} = total crown length (m)

Hasenauer (1997) proposed the logarithmic transformation of both crown radius and predictor variables to control "the variance increase with increasing tree dimensions":

(2.9) $$\ln(r_{\max}) = a + b \cdot \ln(dbh)$$

(2.10) $$\ln(r_{\max}) = a + b \cdot \ln(h)$$

Of the species examined in this study (Norway spruce (*Picea abies* (L.) H. Karst.), silver fir (*Abies alba* Mill.), European larch (*Larix decidua* Mill.), Scots pine (*Pinus sylvestris* L.), black pine (*P. nigra* J.F. Arnold), stone pine (*P. cembra* L.), beech (*Fagus sylvatica* L.), oak (*Quercus* spp.), maple (*Acer* spp.), ash (*Fraxinus* spp.) and lime (*Tilia* spp.)), equation 2.9 gave better results than 2.10, in terms of mean squared error, for all except beech, suggesting that *dbh* is a better predictor of crown radius than total height.

Pretzsch *et al.* (2002), describing the SILVA model, gave the following equation for estimating the crown radius of Norway spruce, silver fir, Scots pine, beech and sessile oak (*Quercus petraea* (Matt.) Liebl.):

(2.11) $$r_{\max} = e^{a + b \cdot \ln(dbh) + c \cdot h + d \cdot \ln(h/dbh)}$$

where a, b, c, d = regression coefficients

This exponential model was also tested by Schröder *et al.* (2005) for Norway spruce, Scots pine, sessile oak, pedunculate oak (*Quercus robur* L.) and beech, along with the following models:

(2.12) $$r_{\max} = (a + b \cdot dbh) \cdot \left(1 - e^{-(dbh/c)^d}\right)$$

(2.13) $$r_{\max} = a + b \cdot (h/dbh) + c \cdot dbh + d \cdot h$$

(2.14) $$r_{\max} = a + b \cdot (dbh/h) \cdot dbh^c$$

Comparisons of observations and simulation outcomes for a mixed, uneven-aged stand over a 28 year period indicated that "the allometric crown width model involving dbh and the dbh-height-ratio [equation 2.12] produces crown width estimates that most closely match the observed distributions in measured stands for all four species. Exponential and linear models, however, showed slight yet insignificant advantages on the individual-tree level" (Schröder *et al.*, 2005).

2.3 Crown length

The length of the live crown can give an indication of the quantity of light reaching the lower portions of a tree, the degree of crowding it is subject to and therefore the competition it faces (or has faced in the past) for growing space (Hasenauer and Monserud, 1996). It is often considered to be an indicator of tree vigour (Dyer and Burkhart, 1987; Temesgen *et al.*, 2005) and of growth response to thinning (Hynynen, 1995). Crown ratio, the ratio of crown length to tree total height, decreases in closed stands with tree age, stand height and the number of trees per unit area (Kantola and Mäkelä, 2004; Fahlvik *et al.*, 2005); if it "decreases to a critical value the rate of wood production decreases greatly" (Kozlowski *et al.*, 1991), and further decrease will lead ultimately to the death of the tree. Beekhuis (1965) observed that crown base height is more or less uniform among trees in a given regular stand of radiata pine (*Pinus radiata* D. Don), and that while "crown height increases as a stand grows taller, the depth of green canopy tends to remain very nearly the same once full canopy closure has been reached, provided stocking does not change". Kohyama *et al.* (1990) explained a similar observation in even-aged stands of Maries fir (*Abies mariesii* Mast.) and Veitch's silver fir (*Abies veitchii* Lindl.) by stating that, "under crowded conditions, the height giving 'compensation point' for assimilation in individual branches is fixed in each stand, and lower (and older) branches than this height have been self-pruned". Patterns of crown base recession are likely to be more complex in irregular stands.

Along with crown radius, crown length is an important determinant of the volume and surface area of the crown. However, consideration must also be given to the length of the crown that is exposed to light (the light crown) and that portion that is shaded (the shade crown) (Assmann, 1970), as the profiles of the light and shade crowns are typically modelled separately (e.g. Pretzsch, 1992; see section 2.4). Crown vertical extent can be modelled in terms of the height to the crown base, the absolute crown length or the crown ratio.

2.3.1 Defining the base of the crown

The most important requirement for crown length measurements is an objective and consistent definition of the base of the crown. Most studies of crown dimensions have concentrated on conifers, so definitions of the crown base for broadleaved species are relatively uncommon. Ward (1964) measured red oak (*Quercus rubra* L.) live crown length "from that general level where the leaf surface began and not where the supporting branch was attached to the main stem". Osada *et al.* (2004) also measured the "lowest leaf height". Mäkinen *et al.* (2003a), however, defined silver birch (*Betula pendula* Roth) crown base as "the lowest living branch no more than 1 m below other living branches". For ash (*Fraxinus excelsior* L.), Cluzeau *et al.* (1994) and Ottorini *et al.* (1996) measured crown length between the tree apex and the base of the branches with the longest horizontal projection; these may be seen as measurements of light crown length rather than total crown length. Ottorini *et al.* (1996) conceded that "the measurement of crown base height was partly based on subjective appreciations". The crown base could also be associated with the "spring of the crown", "the lowest point at which no main stem is distinguishable" (Hamilton, 1975, p. 143).

Many definitions of conifer crown base, at varying levels of detail, have been proposed. Depending on the purpose for which crown data are required, some definitions may be intended to delineate only the main bulk of the crown, while others may aim to encompass the full vertical extent of live foliage. Some authors identify the base of the crown with the lowest live whorl of branches (Hamilton, 1969; Curtis and Reukema, 1970; Siemon *et al.*, 1976; Rollinson, 1988; Maguire and Hann, 1989; Colin and Houllier, 1992; Hynynen, 1995; Gilmore *et al.*, 1996; Hasenauer, 1997; Mäkinen *et al.*, 2003b; Spathelf, 2003). Hamilton (1969) defined the lowest live whorl as the point "where more than half of the branches of the whorl bore green needles" and Curtis and Reukema (1970) identified "the lowest whorl with live branches in at least three quadrants, exclusive of epicormic branches and whorls not continuous with the main crown", an approach adopted by Colin and Houllier (1992). Gilmore *et al.* (1996) stated that the lowest whorl considered to be the base of the live crown must have "three or more live branches", whereas Siemon *et al.* (1976) only required that the lowest green whorl have "a minimum of two live branches". Spathelf (2003) used "the last green whorl with at the most one dead branch from the top of the tree". Rollinson (1988) identified both an upper and a lower crown height, defining the upper crown height as "the height from ground level to the lowest complete whorl of live branches" (for lower crown height, see below). In their study into relationships between crown dimensions and sapwood area at the crown base, Maguire and Hann (1989) recognised three different heights within the crowns of felled Douglas fir; the "crown base (CB), the lowest whorl in the crown that had live branches around at least three quarters of the stem circumference", the "lowest contiguous live whorl (LCLW), the lowest live whorl above which all whorls had at least one live branch", and the "height to live crown (HLC), height to midpoint between CB and LCLW". Mäkinen *et al.* (2003b) identified both the crown base, "the lowest whorl with at least one living branch that is separated from other living whorls above it by no more than one dead whorl", and the lowest dead whorl, "the lowest whorl with at least one branch that is separated from other whorls located above it by one completely self-pruned whorl at the most". Less detailed descriptions of the crown base include "the lowest live contiguous whorl" (Hynynen, 1995) and "the base of the first whorl that was part of the crown" (Hasenauer, 1997).

Other authors associate the base of the crown with a single branch, rather than with a whorl of branches (Dyer and Burkhart, 1987; Sprinz and Burkhart, 1987; Rollinson, 1988; Kohyama *et al.*, 1990; Maguire *et al.*, 1991; Coyea and Margolis, 1992; Short and Burkhart, 1992; Hasenauer and Monserud, 1996; Fahlvik *et al.*, 2005; Rautiainen and Stenberg, 2005). Coyea and Margolis (1992) defined crown base as "the lowest point in the crown below a continuous series of live branches"; in a similar vein, Rautiainen and Stenberg (2005) used "the lowest branch above which there were at least two consecutive living branches". Dyer and Burkhart (1987) and Short and Burkhart (1992) measured the "height to the first significant live branch", while Sprinz and Burkhart (1987) identified the base of the crown with the "first major branch"; unfortunately, no explanation is given of what might constitute a "major" or "significant" branch. Rollinson (1988) defined the lower crown height as "the height from ground level to the lowest live branch on the main stem, excluding epicormics or forks". Kohyama *et al.* (1990) defined the crown base simply as the "height of the lowest living branch", as did Fahlvik *et al.* (2005). Maguire *et al.* (1991) measured "the average height to live branches for a given tree". Hasenauer and Monserud (1996) offered a more detailed description; they measured the height to "the base of the first normal green branch that is part of the crown; this excludes secondary branches (epicormic and adventitious)" and further stipulated that "a single green branch is not the base of the crown if there are at least three dead whorls above it".

Some authors measured both the height to the lowest live branch and the height to the lowest live whorl (Valentine *et al.*, 1994; Deleuze *et al.*, 1996). Conifer crown base definitions which do not explicitly refer to either whorls or branches include "the point where foliage occupied at least three of the four quadrants around the stem" (Canham *et al.*, 1999), "the height of maximum green width" (Warrack, 1959) and even simply the "lowest continuously foliated portions" (Mizoue and Masutani, 2003).

The irregularity of the form of many crowns is a significant impediment to measurements of crown length. One approach to this problem is to measure the heights of whorls with different numbers of live branches (e.g. Maguire and Hann, 1989). Beekhuis (1965), working with radiata pine, instead opted "to visualize any irregular crown transformed into a regular shaped crown of the same effective size, that is, by balancing out all sides and completing partly green whorls at the top, as it were, with green branches taken from lower down the stem". In a similar fashion, Maguire and Hann (1987) undertook "visual reconstruction of the crown, adopting the following two conventions: (1) any gaps in the crown were filled in with branches from below to produce a symmetric, even-based crown; and (2) branches below a subjectively determined minimum vigor were disregarded". Biging and Wensel (1990) also "visually averaged (balanced)" the bottom of the crown. Curtis and Reukema (1970) simply stated that for "a few trees with very lopsided crowns, heights to each half of the crown were measured and averaged".

The lack of consensus between authors gives some indication of the difficulty inherent in establishing a universally applicable definition of the crown base. However strict the definition, there is scope for a great deal of subjectivity in field measurements (Maguire and Hann, 1987; Short and Burkhart, 1992).

2.3.2 *Modelling crown length*

In the absence of long-term crown dimension data, this study concentrates on static models of crown length rather than dynamic models of crown base height increment (e.g. Valentine *et al.*, 1994; Liu *et al.*, 1995; Hann and Hanus, 2004), although Maguire and Hann (1987) have demonstrated that crown base recession can be reconstructed using stem dissection. There are three approaches to modelling total crown length; either the length can be predicted directly, or the height to the crown base can be modelled, or the crown ratio can be modelled, that is, the crown length as a proportion of total tree height. The formats of all the equations below have been standardised to use the same variable and coefficient labels; resulting values are for crown length (L_{total}), height to crown base (*hcb*) or crown ratio (*CR*).

Published crown length models tend to be rather simple. Curtis and Reukema (1970) observed a linear relationship between crown length and stem diameter for Douglas fir:

(2.15) $$L_{total} = a + b \cdot dbh$$

where
L_{total} = total crown length (m)
dbh = diameter at breast height (cm)
a, b = regression coefficients

Curtis and Reukema (1970) noted that differences between treatments in a plantation spacing trial "existed during the period of stand closure", but that after closure "differences among spacings in crown lengths of trees of similar dbh or total height had largely disappeared".

A linear relationship with tree height was used by Gilmore (2001) to model larch (*Larix* spp.) crown length:

(2.16) $$L_{total} = a + b \cdot h$$

where h = total height (m)

Osada *et al.* (2004) noted linear relationships between tree height and crown depth, and Hamilton (1969) also found a "high degree of correlation between crown depth and tree height" for Sitka spruce. Canham *et al.* (1999) used linear functions to model the crown length of species including western hemlock, western red cedar (*Thuja plicata* Donn ex D. Don), amabilis fir (*Abies amabilis* Dougl. ex Forbes), subalpine fir, lodgepole pine, cottonwood (*Populus balsamifera* subsp. *trichocarpa* (Torr. & A. Gray ex Hook.) Brayshaw) and paper birch (*Betula papyrifera* Marshall), but found that intercepts were not significantly different from zero and so simplified the model to give crown length as a proportion of tree height, thus:

$$(2.17) \qquad L_{total} = a \cdot h$$

This model form has the advantage that, as long as the coefficient a never exceeds a value of one, crown length can never be greater than tree height. For equation 2.16, logical model behaviour depends on coefficient values and the range of tree heights used. Equation 2.17, however, may not account for the relatively long crowns of very young trees or the potential variation in crown length in irregular stands.

Based on the observation that crown length remains relatively constant after canopy closure in regular stands, "provided stocking does not change", Beekhuis (1965) proposed the following model:

$$(2.18) \qquad L_{total} = a + b \cdot S$$

where S = triangular spacing (m)

This relationship relies on a relatively regular stand structure and a narrow range of tree heights, although measures of local stocking could be substituted for triangular spacing in irregular stands with more varied canopy structure. Even in regular stands, careful parameterisation would be required to avoid L_{total} values greater than tree height.

Short and Burkhart (1992) postulated that "incrementing crown-height through time, much like diameter and height are incremented, would improve crown size estimates and would subsequently improve tree growth and mortality prediction". The following models, however, provide static estimates of height to crown base. Hasenauer (1997) proposed a simple model based on tree height:

$$(2.19) \qquad \ln(hcb) = a + b \cdot \ln(h)$$

where hcb = height to crown base (m)

For the SILVA model, Pretzsch *et al.* (2002) described a more complicated model using both tree height and stem diameter:

$$(2.20) \qquad hcb = h \cdot \left(1 - e^{-(a + b \cdot (h/dbh) + c \cdot dbh)}\right)$$

where a, b, c = regression coefficients

Although Pretzsch *et al.* (2002) did not specify coefficient constraints, the model exponent must be zero or negative if hcb is to be constrained between zero and tree height. Dyer and Burkhart (1987) specified positive coefficients in their model for loblolly pine, which also incorporated stand age:

$$(2.21) \qquad hcb = h \cdot e^{-\left(a + b \cdot A_s^{-1}\right)(dbh/h)}$$

where A_s = stand age (years)

In this case, "estimated crown height will always be between zero and total tree height, will decrease with an increasing taper... and will increase and level off with increasing age" (Dyer and Burkhart, 1987). The variable stand age is not relevant to irregular stands. Colin and Houllier (1992) developed a model for Norway spruce with similar inputs, but incorporating tree age in place of stand age:

$$(2.22) \qquad hcb = h \cdot \left(1 - a - e^{-b \cdot A_t^{1.5}} - c \cdot (h/dbh) - d \cdot h^2\right)$$

where A_t = tree age (years)
a, b, c, d = regression coefficients

Instead of age, Hann and Hanus (2004) used measures of competition and stand density in their allometric model for Douglas fir:

(2.23) $$hcb = h/\left(1 + e^{a+b\cdot h+c\cdot CCFL+d\cdot \ln(BA)+f\cdot (dbh/h)}\right)$$

where BA = stand basal area (m^2 ha^{-1})
$CCFL$ = crown competition factor of larger trees
a, b, c, d, f = regression coefficients

This is a more robust model form; whatever the value of the exponent, *hcb* cannot be less than zero or greater than *h*.

Dyer and Burkhart (1987) and Colin and Houllier (1992) also produced versions of their *hcb* models which gave crown ratio as the output (equations 2.24 and 2.25 respectively).

(2.24) $$CR = 1 - e^{-\left(a+b\cdot A_s^{-1}\right)(dbh/h)}$$

(2.25) $$CR(\%) = 100 \cdot \left(a + e^{-b\cdot A_t^{1.5}} + c \cdot (h/dbh) + d \cdot h^2\right)$$

where CR = crown ratio

The negative exponent in equation 2.24 effectively constrains the model to give logical *CR* values between zero and unity. Equation 2.25 relies on appropriate parameterisation to control model outcomes.

The Norway spruce and silver fir crown ratio model of Spathelf (2003) was derived by stepwise regression using the variables *dbh*, age at breast height, height increment and Hegyi's competition index (with basal area factor 4 relascope competitor selection), and transformations thereof. Logical behaviour of the resulting model depends on careful parameterisation:

(2.26) $$CR(\%) = a + b \cdot \Delta h + c \cdot Hg_{Rel}$$

where Δh = height increment (m)
Hg_{Rel} = Hegyi competition index for competitors selected by relascope

Spathelf (2003) noted that "[w]ith increasing competition crown recession is increasing too. Trees of equal competition status but with higher height increment, which means more vigorous trees, exhibit higher crown recession rates."

Holdaway (1986) stated that "the [crown] ratio can be estimated using a nonlinear model combining stand basal area... and initial tree diameter... The first term reflects the importance of competition on crown ratio; the second term differentiates among trees of different sizes". Again, this model requires careful parameterisation to ensure logical outputs.

$$(2.27) \qquad CR = \frac{a}{1 + b \cdot BA} + c \cdot \left(1 - e^{-d \cdot dbh}\right)$$

In their crown ratio model for birch, Mäkinen *et al.* (2003a) also included both individual tree dimensions and stand basal area. They used logistic regression to constrain values of *CR*:

$$(2.28) \qquad \ln\left(\frac{CR}{1 - CR}\right) = a + b \cdot dbh + c \cdot (h/dbh) + d \cdot BA$$

A similar approach was taken by Mäkinen *et al.* (2003b) to modelling Norway spruce crown ratio:

$$(2.29) \qquad \ln\left(\frac{CR}{1 - CR}\right) = a + b \cdot dbh + c \cdot h_{dom} + d \cdot PL$$

where h_{dom} = stand dominant height (m)
PL = peatland dummy variable (0, mineral soil; 1, peatland)

Hasenauer and Monserud (1996) and Temesgen *et al.* (2005) took a different mathematical approach to constraining crown ratio to logical values (equation 2.30). The model is exceptionally detailed, incorporating separate functions for individual tree size (equation 2.31), competition (equation 2.32) and site factors (equation 2.33). Temesgen *et al.* (2005) stated that, "[s]ince diameter differences are largely due to competition, much of the effects of competition on CR are likely already accounted for by the tree size variables, even for multi-species and multi-layered stands"; this was borne out by their results, which showed that "[s]ize variables were, generally, the best predictors of CR variability".

(2.30) $$CR = \frac{1}{1 + e^{-(a + b \cdot SIZE + c \cdot COMP + d \cdot SITE)}}$$

(2.31) $$b \cdot SIZE = b_1 \cdot (h/dbh) + b_2 \cdot h + b_3 \cdot dbh^2$$

(2.32) $$c \cdot COMP = c_1 \cdot BAL + c_2 \cdot \ln(CCF)$$

(2.33) $$d \cdot SITE = d_1 \cdot Z + d_2 \cdot Z^2 + d_3 \cdot sl + d_4 \cdot sl^2 + d_5 \cdot sl \cdot \sin(az) + d_6 \cdot sl \cdot \cos(az)$$

where
BAL = basal area of larger trees (m² ha^{-1})
CCF = crown competition factor
Z = elevation (m)
sl = slope (tangent of slope angle, % / 100)
az = azimuth of aspect (radians)
$b_1 \ldots b_3$ = regression coefficients
$c_1 \ldots c_2$ = regression coefficients
$d_1 \ldots d_6$ = regression coefficients

This is by far the most complex crown ratio model. At the opposite extreme, Kramer (1966) produced stand level models for Norway spruce (equation 2.34), Sitka spruce and Douglas fir (equation 2.35) with only one independent variable:

(2.34) $$CR(\%) = a + (100 - a) \cdot e^{0.5 \cdot (1/b) \cdot (h_{100} - c)^2}$$

(2.35) $$CR(\%) = a \cdot e^{b \cdot h_{100}}$$

where h_{100} = stand top height (m)

With appropriate parameter constraints, these models can produce properly constrained crown ratio values; Kramer (1966) discussed the role of each parameter in determining model behaviour. The models are based on work in even-aged plantations, however, and are unlikely to be suitable for irregular stands where crown ratio can vary greatly between trees of different sizes.

There exists a wide range of models to predict vertical crown extent, with a great many potential independent variables. Importantly, however, there are a number of model forms which produce or can be modified to produce strictly constrained and logical outputs, in the form of total crown length, height to crown base or crown ratio.

2.4 Crown profile

Measures of photosynthetic capacity such as crown volume (Sprinz and Burkhart, 1987) and exposed surface area (Smith, 1994), and competition indices such as the KKL index in SILVA (Pretzsch *et al.*, 2002) depend on the quantification of both the size and the shape of the crown. Crown shape is determined by "the inherent growth form of the species and environmental influences" (Oliver and Larson, 1996). Horn (1971) noted that "[t]he shape of a tree in the forest is largely determined by the shape of the space it fills". Neighbouring crowns influence each other through physical abrasion and shading (Oliver and Larson, 1996), but the shape of those portions of the crown growing free from competition is generally no different to that of an open-grown tree of the same species and size (Honer, 1971; Cluzeau *et al.*, 1994).

Crown shape is most readily modelled in terms of crown profile. Roeh and Maguire (1997) defined the crown profile as "the curve connecting the tips of either the largest or average branch within each whorl, when viewed on a plane longitudinally bisecting the stem and crown"; the shape of the crown "is dictated by the relative differences in growth rate between the terminal and lateral leaders and among lateral leaders at successive depths into crown". Kozlowski (1971a) described two general crown forms, excurrent and deliquescent, on the basis of differential shoot growth:

> In most gymnosperms and a few angiosperms the terminal leader grows more each year than the lateral branches below it, resulting in a conical crown and a single central stem. This pattern of branching results in an excurrent tree form. In most angiosperm trees, the lateral branches grow almost as fast as, or faster than, the terminal leader, resulting in a growth habit described as decurrent or deliquescent.

For a given tree, the relative growth of terminal and lateral shoots, and therefore the shape of the crown, may be influenced largely by shading (Greis and Kellomäki, 1981; Oliver and Larson, 1996) and tree age (Horn, 1971; Deleuze *et al.*, 1996; Oliver and Larson, 1996).

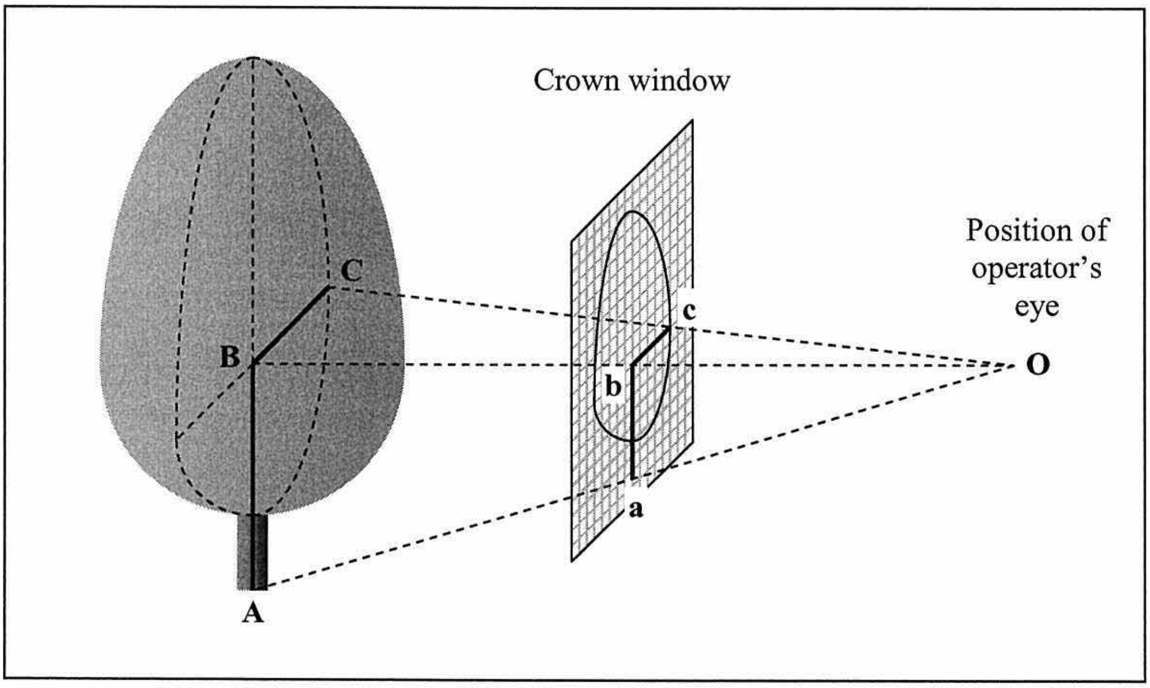
Assmann (1970, pp. 113-4) described average crown forms of dominant Norway spruce, Scots pine, beech and oak trees in moderately thinned, closely stocked stands. He noted that "the largest diameter lies approximately two-thirds from the top" for the conifer species, and "at between one-third and one-half the crown height measured from the top" for the broadleaves. Canham *et al.* (1999) observed that maximum crown radius occurs "at or near the bottom of the crown" for conifers and "much closer to the top of the crowns" for broadleaves, and Kantola and Mäkelä (2004) stated that Norway spruce crowns "were widest at the very base of the living crown". The widest point of the crown separates the part exposed to light from the shaded part, and these light and shade crowns may differ in shape; this is reflected in the crown shape models of Pretzsch *et al.* (2002). Assmann (1970) recognised that the relative length of the light crown is greater "[t]he more the crown is open to the sky because of social dominance or in consequence of a disengagement thinning".

2.4.1 Measuring crown profile

Direct measurements of crown profiles are usually acquired by destructive sampling (Honer, 1971; Hashimoto, 1991; Cluzeau *et al.*, 1994; Deleuze *et al.*, 1996), because of the difficulties of measuring large standing trees. Destructive sampling typically involves systematically dividing the stems of felled trees into sections, setting these sections upright so that branches hang naturally, and measuring branch characteristics (height to branch base and tip, branch length and horizontal branch extension) for some or all branches in each section. Kantola and Mäkelä (2004) used a similar sampling method to gather branch length and foliage mass data for Norway spruce crowns. Honer (1971) also measured crown radii for each section in four cardinal directions, referring to a mark made on the north side of the stem prior to felling. Cluzeau *et al.* (1994), working with ash, and Deleuze *et al.* (1996), working with Norway spruce, recreated stem growth and branch elongation by measuring to bud scale scars; this greatly increased the volume of crown data available, although Cluzeau *et al.* (1994) noted that it was not possible to reconstruct past branch angles. Destructive sampling does have the disadvantage that crowns may be damaged during felling.

Standing trees can be measured directly if suitable equipment is available; Song *et al.* (2004) measured crown radii "at various vertical heights from the crown's top to its base, at up to four cardinal directions" in an old-growth Douglas fir forest using a crane with "a 75-m vertical reach and an 85-m radius" to access the canopy. A number of indirect measurement methods may also be employed. Rautiainen and Stenberg (2005) calculated Scots pine crown radii at eight different heights in the crown from the distance from the observer to the tree, the height of the measurement point and the angle "between the tree trunk center and crown outmost point at that height". Biging and Gill (1997) were forced to adopt a similar approach when operational difficulties prevented them from measuring 3-D co-ordinates of branch tips using a Criterion 400 Survey Laser Instrument (Laser Technology Inc.). The "crown window" described by Hussein *et al.* (2000) relies on the equivalence of the shape of a tree and its outline as viewed through a transparent sheet held parallel to the stem axis. The outline seen through the crown window can be scaled according to a measured tree height or crown length, so that crown radii measured on the outline can be converted to real-world values (Fig. 2.4). Hussein *et al.* (2000) drew crown profiles onto transparencies and took measurements from digitised versions. The device was found to be accurate provided that it was set up correctly (exactly parallel to the stem, and at a suitable horizontal distance) and that the operator's head did not move during use (a head stabiliser was fitted to avoid this). Another indirect approach to assessing crown profile is to derive measurements from photographs using photogrammetric techniques (Remphrey *et al.*, 1987; Riedel, 2002; Phattaralerphong and Sinoquet, 2005).

Fig. 2.4 The "crown window". Adapted from Hussein *et al.* (2000). Crown radius BC at height AB in the crown is given by radius bc at height ab in the crown window image scaled by tree total height.



2.4.2 *Photogrammetry*

Konecny (2003, p. 106) stated that "[p]hotogrammetry concerns itself with the geometric measurement of objects in analogue or digital images". Most applications of photogrammetry in forestry have involved aerial photography and the delineation of individual crowns. As well as simply quantifying tree cover (Bai *et al.*, 2005), aerial photographs can be used to map the forest canopy surface and canopy gaps (Henbo *et al.*, 2004; Jan, 2005), and, in combination with models to predict stem diameter from crown dimensions, can provide inventory data such as *dbh*, tree height and stand basal area (Minor, 1951; Bonnor, 1964; Bonnor, 1968; Kalliovirta and Tokola, 2005; Zagalikis *et al.*, 2005).

Ground-based photogrammetry has been less widely used in forestry. Photogrammetric techniques can be used to assess characteristics of the stem, such as volume and taper (Gaffrey *et al.*, 2001; Dean, 2003), but they can also be used to measure crowns. Nakayama and Nagashima (1963) used terrestrial stereo photographs to measure sugi (*Cryptomeria japonica* (L. f.) D. Don) crown diameters, while Koike (1985) reconstructed the two-dimensional distribution of foliage density in sections through tree crowns and forest canopies using hemispherical photographs. Koch and Reidelstürz (1998) demonstrated that stereo photographs could be used to model the branching structure of oak and the crown surface area and volume for poplar (*Populus* spp.). To overcome the difficulties of working with tall trees in closed canopies, Mizoue and Masutani (2003) felled hinoki cypress (*Chamaecyparis obtusa* (Siebold and Zucc.) Endl.) sample trees, re-erected the crowns and photographed them against a white background in order to assess crown transparency, by comparing silhouette and outline crown images.

Terrestrial photogrammetry can also yield crown shape information suitable for the modelling of crown profiles. Remphrey *et al.* (1987) derived crown dimension and shape data from orthogonal photographs of street trees, scaled using a measuring pole; as measurements were based on the outline of the crown, this is essentially the photogrammetric equivalent of using a crown window. In a far more complex approach, Phattaralerphong and Sinoquet (2005) generated detailed models of crown shape and volume by combining data from multiple photographs classified into vegetated and nonvegetated areas. Riedel (2002) tested "multi-picture triangulation" as a non-destructive method for gathering three-dimensional data on the structure of beech and Norway spruce plants, using the commercially available software PhotoModeler Pro 4.0. By marking the same object, such as a branch node, on multiple photographs, the location of the object in 3-D space can be calculated based on the intersection of light rays. Riedel (2002) was able to extract large quantities of data from photographs, such as shoot lengths and diameters, branching angles and crown projection area, but branch tip co-ordinates calculated by PhotoModeler could also be used to define crown profiles.

2.4.3 Modelling crown profile

Various approaches to modelling crown profile have been taken in the past. Many authors have characterised crowns as simple geometric shapes, such as rotational paraboloids or ellipsoids, or cones (Hashimoto, 1991; Jack and Long, 1991; Reid *et al.*, 2004; Pelt and Nadkarni, 2004). Others have used far more complex methods. Cluzeau *et al.* (1995) generated three-dimensional convex hulls based on direct field measurements of ash branch architecture, in preference to using "axisymmetrical shapes" which "impose heavy constraints on the representation of the crown boundary".

For the purposes of calculating competition indices such as the KKL index (Pretzsch *et al.*, 2002), simplified, rotationally symmetrical representations of crown profiles are acceptable. A crown profile model should give a value of crown radius, r, for a known vertical position in the crown, measured from the crown tip (D_{tip}), the crown base (D_{base}) or the height of maximum crown radius ($Dr_{\max}$), as illustrated in Fig. 2.2. The simplest models are not constrained in any way by the inclusion of variables representing crown length or maximum crown radius. Honer (1971), for example, used a model with only tree height and D_{tip} as independent variables:

$$r = a \cdot D_{tip} + b \cdot D_{tip} \cdot h + c \cdot \left(D_{tip}^{\ 2} / h\right) + d \cdot D_{tip}^{\ 2} \qquad (2.36)$$

where r = crown radius (m)
D_{tip} = vertical distance from crown tip (m)
h = total height (m)
a, b, c, d = regression coefficients

Mitchell (1975) used only D_{tip} in a crown profile model for Douglas fir:

(2.37) $$r = a \cdot \ln((D_{tip}/b)+1)$$

Remphrey *et al.* (1987) simply fitted polynomial regression lines to crown diameter data. Pretzsch's (1992) models were slightly more sophisticated. Separate models were applied to light and shade crowns. Although the models themselves were very basic in form, parameter values were calculated using sub-models which ensured that they behaved realistically, in that the results of light and shade crown models coincided at the point of maximum crown radius. Equation 2.38 models light crown profile as a paraboloid, and equation 2.39 models the shade crown as a truncated cone:

(2.38) $$r = a \cdot D_{tip}{}^{b}$$

(2.39) $$r = a + b \cdot D_{base}$$

where D_{base} = vertical distance from crown base (m)

It is possible to produce similar models which explicitly constrain results so that $r = r_{\max}$ at the point of maximum crown radius:

(2.40) $$r = r_{\max} \cdot (D_{tip}/L_{light})^{a}$$

(2.41) $$r = a \cdot r_{\max} + (1-a) \cdot r_{\max} \cdot (D_{base}/L_{shade})$$

where $r_{\max}$ = maximum crown radius (m)
L_{light} = light crown length (m)
L_{shade} = shade crown length (m)

Several authors have produced models, constrained by maximum crown radius, based on the equation for an ellipse (Kändler, 1986; Seifert, 2002, pers. comm.; MacFarlane *et al.*, 2003; Rautiainen and Stenberg, 2005). Kändler's (1986) original equation (equation 2.42) can be re-arranged to give crown radius as the product (equation 2.43):

(2.42) $$Dr_{\max} = L \cdot (1-(r/r_{\max})^{a})^{b}$$

(2.43) $$r = r_{\max} \cdot (1-(Dr_{\max}/L)^{a})^{b}$$

where Dr_{max} = vertical distance from height of maximum crown radius (m)
L = light or shade crown length (m)

Note that a and b are not equivalent between these two equations. Seifert (2002, pers. comm.) developed a model for Norway spruce light and shade crowns, originally expressed as in equation 2.44; this can be re-arranged to give a model very similar to Kändler's (1986), but with only one regression coefficient (equation 2.45):

(2.44) $$r = -1 \cdot r_{max} \cdot (Dr_{max}/L)^a + r_{max}$$

(2.45) $$r = r_{max} \cdot \left(1 - (Dr_{max}/L)^a\right)$$

MacFarlane *et al.* (2003) based loblolly pine light and shade crown shapes on rotations of quarter ellipses (equation 2.46); re-arranged to give crown radius as the product, this model is again similar to Kändler's (1986), with Kändler's b parameter replaced with the reciprocal of a (equation 2.47):

(2.46) $$\left(\frac{r}{r_{max}}\right)^a + \left(\frac{Dr_{max}}{L}\right)^a = 1$$

(2.47) $$r = r_{max} \cdot \left(1 - (Dr_{max}/L)^a\right)^{(1/a)}$$

Unusually, MacFarlane *et al.* (2003) also presented a model to calculate the relative height of maximum crown radius within the crown, as a percentage of total crown length; this can be seen as a shade crown ratio model:

(2.48) $$\frac{L_{shade}}{L_{total}}(\%) = \left(\frac{-2 \cdot a}{b}\right)^{0.5}$$

(2.49) $$a = -4.5121 + 0.5176 \cdot \overline{dbh} + 4.3529 \cdot \overline{CR}$$

(2.50) $$b = -4.4749 - 0.4985 \cdot \overline{dbh} - 6.0410 \cdot \overline{CR} - 0.00175 \cdot A_s$$

where L_{total} = total crown length (m)
$\overline{dbh}$ = stand mean *dbh* (cm)
$\overline{CR}$ = stand mean crown ratio
A_s = stand age (years)

This approach obviously assumes that all trees within the stand have the same ratio of light crown length to shade crown length.

The Scots pine crown profile model used by Rautiainen and Stenberg (2005) is also based on the equation for an ellipse (equation 2.46), but is re-arranged slightly differently to the model of MacFarlane *et al.* (2003):

$$(2.51) \qquad r = \left(r_{\max}{}^{a} \cdot \left(1 - \left(Dr_{\max} / L\right)^{a}\right)\right)^{(1/a)}$$

Kändler's (1986) two parameter model (equation 2.43) is more flexible than the single parameter models of Seifert (2002, pers. comm.), MacFarlane *et al.* (2003) and Rautiainen and Stenberg (2005) (equations 2.45, 2.47 and 2.51); Kändler illustrated some of the range of crown shapes produced by the model with different parameter values (Kändler, 1986, p. 47).

3 MATERIALS & METHODS

3.1 Crown survey

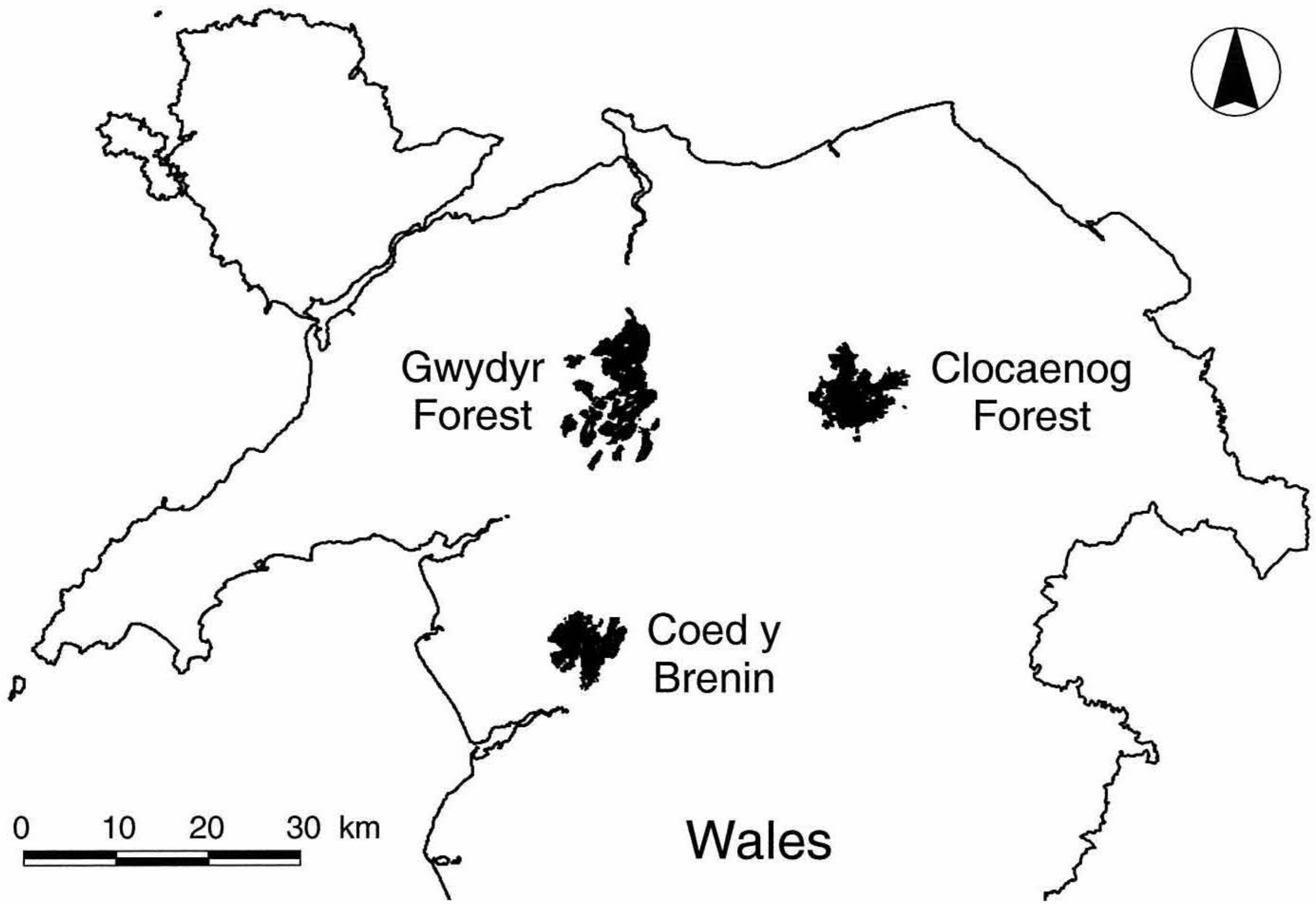
The aim of the crown survey was to collect baseline crown dimension and shape data for a broad sample of trees of both target species within fully mapped and inventoried plots. This strategy meant that crown characteristics could be related not only to individual tree variables such as stem diameter, but also to spatial variables quantifying relationships with neighbouring trees.

3.1.1 Permanent sample plot establishment and inventory

Most of the data used in this study were collected in five of the *Tyfiant Coed* sample plots in National Assembly forests: two at Cefn Du, Clocaenog Forest, Coed y Gororau Forest District (CLG1 and CLG2); two at Ganllwyd, Coed y Brenin, Coed y Mynydd Forest District (CYB1 and CYB2); and one at Pen-yr-allt Ganol, Gwydyr Forest, Coed y Mynydd Forest District (GWY1). Plot locations are shown in Fig. 3.1.

The first plots to be established, GWY1, CLG1 and CLG2, share a standard layout, each being a square with an area of one hectare and edges 100 m long. Plots CYB1 and CYB2 are smaller and rectangular to fit into smaller stands. The plots are located so as to be separated from roads, rides and stand edges by a buffer zone of at least 20 m. A Topcon GTS-229 electronic total station (Topcon (Great Britain) Ltd.) was used to map accurately the location of the plot boundaries and to set up a network of permanently marked stations throughout each plot.

Fig. 3.1 **Permanent sample plot locations. The five *Tyfiant Coed* sample plots are located in Clocaenog Forest (plots CLG1 and CLG2), Coed y Brenin (CYB1 and CYB2) and Gwydyr Forest (GWY1).**



All trees equal to or greater than 5 cm *dbh* within the plots were numbered (with metal tags, painted numbers or both) and marked with painted *dbh* lines. These trees were then mapped in three dimensions (giving X, Y and Z Cartesian co-ordinates for each tree) with the total station, using the network of permanent stations for orientation. For each tree, a record was made of its species, *dbh* (measured to the nearest 0.1 cm using a research grade *dbh* tape), and two measurements each of total height and height to crown base (measured to the nearest 0.1 m using a Haglöf Vertex III (Haglöf Sweden AB)). Arithmetic means were calculated for total height and height to crown base. Measurements followed the conventions in the Forestry Commission's *Forest Mensuration Handbook* (Hamilton, 1975).

Manual brashing was carried out in plots CYB1 and CYB2 to improve access and visibility for mapping and mensuration. To further improve survey conditions, and to promote suppressed birch, frame tree thinnings (Spiecker *et al.*, 2004, p. 144) were carried out in both plots. Felled trees were measured for *dbh*, height measurements were taken using a tape, and each tree's number tag was transferred to its stump so that tree positions could be mapped after the operation.

3.1.2 Permanent sample plot descriptions

The five plots cover a wide range of stand structures. The Clocaenog plots are in relatively uniform stands of Sitka spruce planted in 1951, although plot CLG2 includes an area of lodgepole pine on a hillock. Both plots show extensive natural regeneration, primarily of Sitka spruce but also including western hemlock and small numbers of broadleaved trees; this regeneration is both more abundant and more advanced in CLG2. The Coed y Brenin plots are more mixed, with many naturally-regenerated broadleaved species in the overstorey in addition to the conifers planted in 1970 (CYB1) and 1972 (CYB2). Plot CYB1 has an overstorey of Sitka spruce and birch with some oak (*Quercus* spp.) and Douglas fir, and an understorey of birch, oak, rowan (*Sorbus aucuparia* L.) and willow (*Salix* spp.). Plot CYB2 has an overstorey of Sitka spruce, western red cedar and birch with some oak and Douglas fir, and an understorey of birch, oak, rowan and willow. Plot GWY1 in Gwydyr Forest is the most diverse of the five, with an overstorey of Scots pine and Sitka spruce planted in 1924 and naturally-regenerated birch, and an understorey mainly of birch, rowan, oak and western hemlock.

Basic plot data are summarised in Table 3.1. These data reveal the status of birch and spruce in each plot. In plots CYB1, CYB2 and GWY1, birch trees make up 33-39 % of the stem count but only 3-13 % of the basal area; overstorey birch in the Coed y Brenin plots are generally suppressed, and other birch in all three plots are generally small understorey trees. The Clocaenog plots are dominated by Sitka spruce. Spruce in the Coed y Brenin plots make up less than half of the stem count but the majority of the basal area, the remainder of the stocking being accounted for by the naturally regenerated understorey and a small number of canopy trees of other species (such as western red cedar in CYB2). Spruce is a relatively minor component of GWY1, although the overstorey status of many of the trees is shown by the difference in the proportions of stocking and basal area they account for.

Table 3.1 Permanent sample plot summaries. Stocking and basal area figures for plots CYB1 and CYB2 are pre-thinning.

Plot		CLG1	CLG2	CYB1	CYB2	GWY1
UK grid reference		SJ 042 539	SJ 044 541	SH 720 250	SH 720 254	SH 784 579
Elevation (m asl)		390	400	210	250	230
Plot area (ha)		1.00	1.00	0.10	0.26	1.03
Stocking (stems ≥ 5 cm *dbh* per ha)	Birch	0 (0 %)	0 (0 %)	1060 (39 %)	754 (33 %)	173 (35 %)
	Sitka spruce	291 (100 %)	253 (79 %)	1130 (42 %)	1112 (48 %)	47 (9 %)
	Other species	0 (0 %)	67 (21 %)	510 (19 %)	431 (19 %)	275 (56 %)
	Total	291	320	2700	2296	494
Basal area (m^2 per ha)	Birch	0 (0 %)	0 (0 %)	6 (13 %)	6 (12 %)	1 (3 %)
	Sitka spruce	30 (100 %)	27 (91 %)	35 (79 %)	33 (70 %)	6 (19 %)
	Other species	0 (0 %)	3 (9 %)	4 (8 %)	8 (18 %)	24 (78 %)
	Total	30	30	45	47	31

Example stem maps for plots CLG2 and GWY1 are given in Fig. 3.2. CLG2 is a relatively regular spruce monoculture with a small area of lodgepole pine, whereas GWY1 has a more open and varied structure with two main overstorey species and an extensive, naturally-regenerated understorey composed primarily of birch.

Fig. 3.2 Example permanent sample plot stem maps. Plot edges are measured in metres. Symbol widths are proportional to *dbh*.

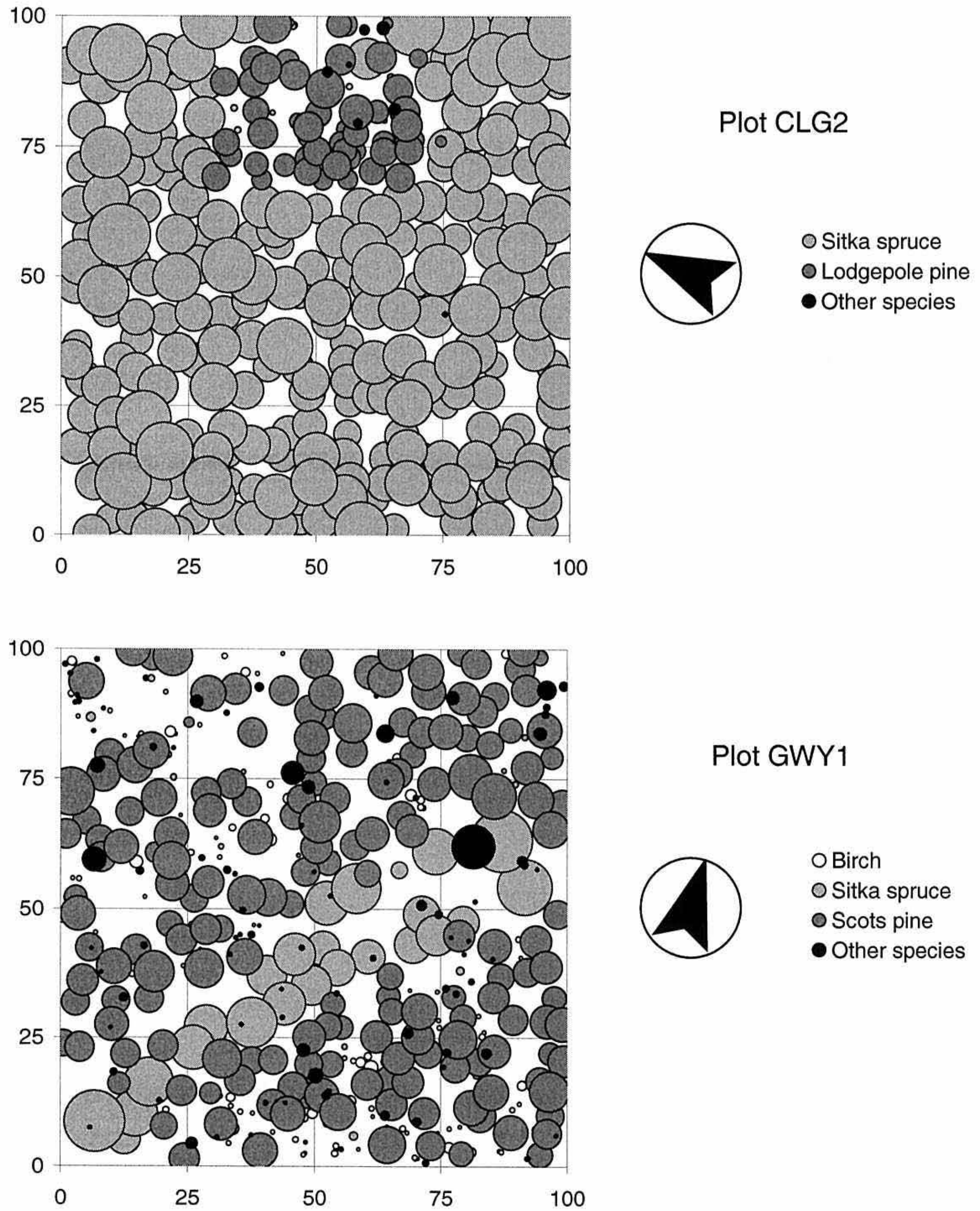
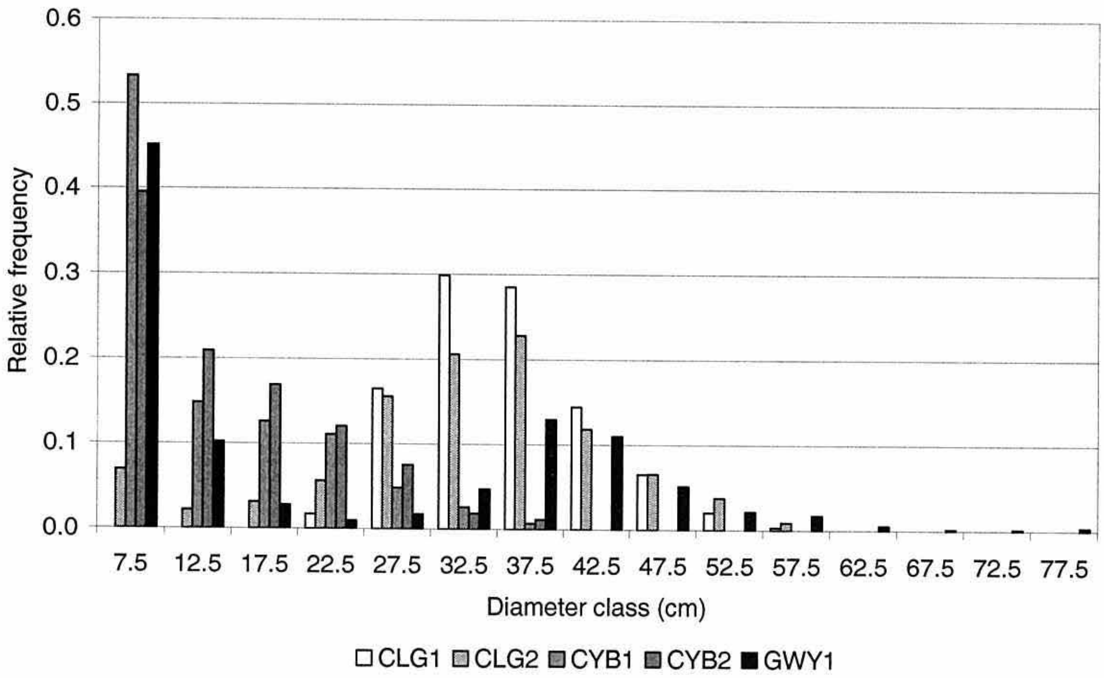


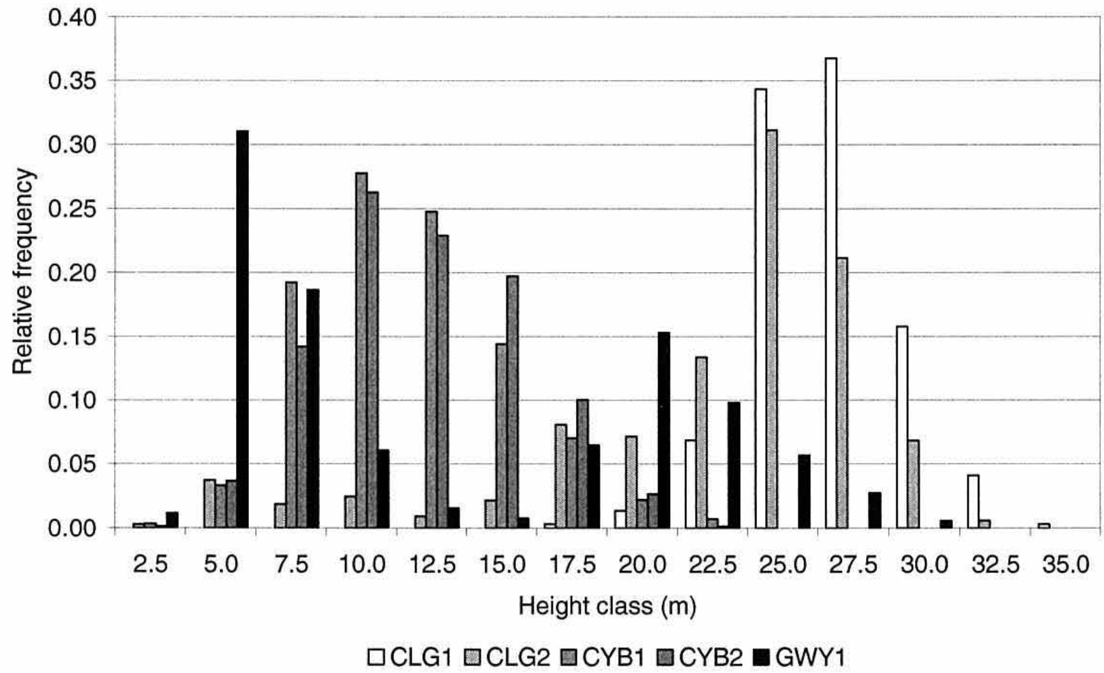
Fig. 3.3 shows diameter distributions for the permanent sample plots. Plot CLG1, being an even-aged monoculture, has a distribution of diameter classes similar to a normal distribution. CLG2 also has a bell-shaped distribution, but with some small diameter natural regeneration developing below the spruce and pine canopy. The distributions for CYB1 and CYB2 are heavily skewed towards the smaller size classes, reflecting the large quantities of natural regeneration in the understorey, including birch, oak, rowan and multi-stemmed willow; these small stems far outnumber the canopy birch, Sitka spruce and, in CYB2, western red cedar. Plot GWY1 shows by far the greatest range of tree dimensions. A bell-shaped distribution of overstorey trees may be observed with a mean *dbh* around 40 cm, with a small number of extremely large outliers; although the canopy is composed primarily of Scots pine, the majority of these outliers are Sitka spruce. A peak in the smallest size class, constituting nearly half of the stems in the plot, represents the prolific natural regeneration; most of this regeneration is of birch, but many other broadleaf and conifer species are also present in small numbers.

Fig. 3.3 Permanent sample plot inventory diameter distributions, showing the proportion of stems in each plot occurring in 5 cm *dbh* classes.



Height distributions (Fig. 3.4) show similar patterns. The Clocaenog plots have normal distributions of canopy tree heights, but CLG2 has a long and irregular tail in the lower height classes; stems between 10 and 20 m in height are mostly lodgepole pine on high ground on the eastern edge of the plot, while smaller trees are naturally-regenerated spruce, rowan and western hemlock. Height distributions are less skewed in the Coed y Brenin plots than diameter distributions, presumably because diameter growth of small, suppressed trees is affected more by competition than height growth. This effect is not apparent in the more open plot GWY1, where the height class distribution follows the diameter distribution quite closely and is truncated below the 5 m class just as the *dbh* distribution is at the 5 cm cut-off. The distributions diverge in the higher classes, where height does not show the same range of outliers; the trees of exceptional girth, being relatively widely spaced, have lower, more stable height:diameter ratios.

Fig. 3.4 Permanent sample plot inventory height distributions, showing the proportion of stems in each plot occurring in 2.5 m total height classes.



3.1.3 *Crown survey sampling strategy and direct crown measurements*

Direct measurements of gross crown dimensions were carried out on random samples of birch and Sitka spruce in plots CLG1, CLG2, CYB1, CYB2 and GWY1. In order to avoid edge effects in the calculation of spatial variables for sample trees (see section 3.5), buffer strips around the margins of the plots were excluded from sampling. These strips were 10 m wide in 1 ha plots (to accommodate 0.02 ha circular samples of 7.98 m radius), and 6 m wide in the smaller Coed y Brenin plots (5.64 m radius samples). Sample sizes are shown in Table 3.2. In GWY1, all 29 eligible spruce were sampled.

Table 3.2 Number of trees in crown survey samples.

	Species	
Plot	Birch	Sitka spruce
CLG1	-	50
CLG2	-	25
CYB1	25	25
CYB2	25	25
GWY1	25	29
Total	75	154

The survey was carried out during August 2003 (CLG and CYB spruce), May-June 2004 (GWY spruce) and August-September 2004 (birch), following the crown measurement protocol in Appendix I. This yielded eight measurements of maximum crown radius, two of total height and two of height to crown base per tree. For each tree, quadratic mean maximum crown radius and arithmetic mean total height and height to crown base were calculated. Mean height to crown base was subtracted from mean height to give total crown length.

Uniformity in crown shape was assessed by calculating the coefficient of variation (*CV*) of the radius measurements for each tree (Francis, 1986); a perfectly circular crown would have a *CV* of zero. Crown irregularity was also quantified by calculating "relative canopy displacement" (Muth and Bazzaz, 2003). Crown radii in known directions were converted into a series of vertices defining a crown polygon, with the tree stem as the origin of the co-ordinate system. The area of each polygon and the co-ordinates of its centroid (or centre of mass) were calculated as follows:

(3.1) $$A = \frac{1}{2} \cdot \sum_{i=0}^{n-1} (X_i \cdot Y_{i+1} - X_{i+1} \cdot Y_i)$$

(3.2) $$X_C = \frac{1}{6A} \cdot \sum_{i=0}^{n-1} (X_i + X_{i+1}) \cdot (X_i \cdot Y_{i+1} - X_{i+1} \cdot Y_i)$$

(3.3) $$Y_C = \frac{1}{6A} \cdot \sum_{i=0}^{n-1} (Y_i + Y_{i+1}) \cdot (X_i \cdot Y_{i+1} - X_{i+1} \cdot Y_i)$$

where
A = crown polygon area (m^2)
X_C = crown polygon centroid X co-ordinate (m)
Y_C = crown polygon centroid Y co-ordinate (m)
X_i = ith crown vertex X co-ordinate (m)
Y_i = ith crown vertex Y co-ordinate (m)
n = number of vertices

These equations all assume a closed polygon, so that the nth vertex is the same as the 0th vertex. Relative canopy displacement (*RCD*) is defined as "the distance between stem position and canopy center of mass divided by the mean of the eight canopy extent measurements" (Muth and Bazzaz, 2003). In this case, calculations were simplified by the fact the tree stem was at the origin of the co-ordinate system.

(3.4) $$RCD = \frac{\sqrt{X_C^{\,2} + Y_C^{\,2}}}{\bar{r}_{max}}$$

where $\bar{r}_{max}$ = arithmetic mean maximum crown radius (m)

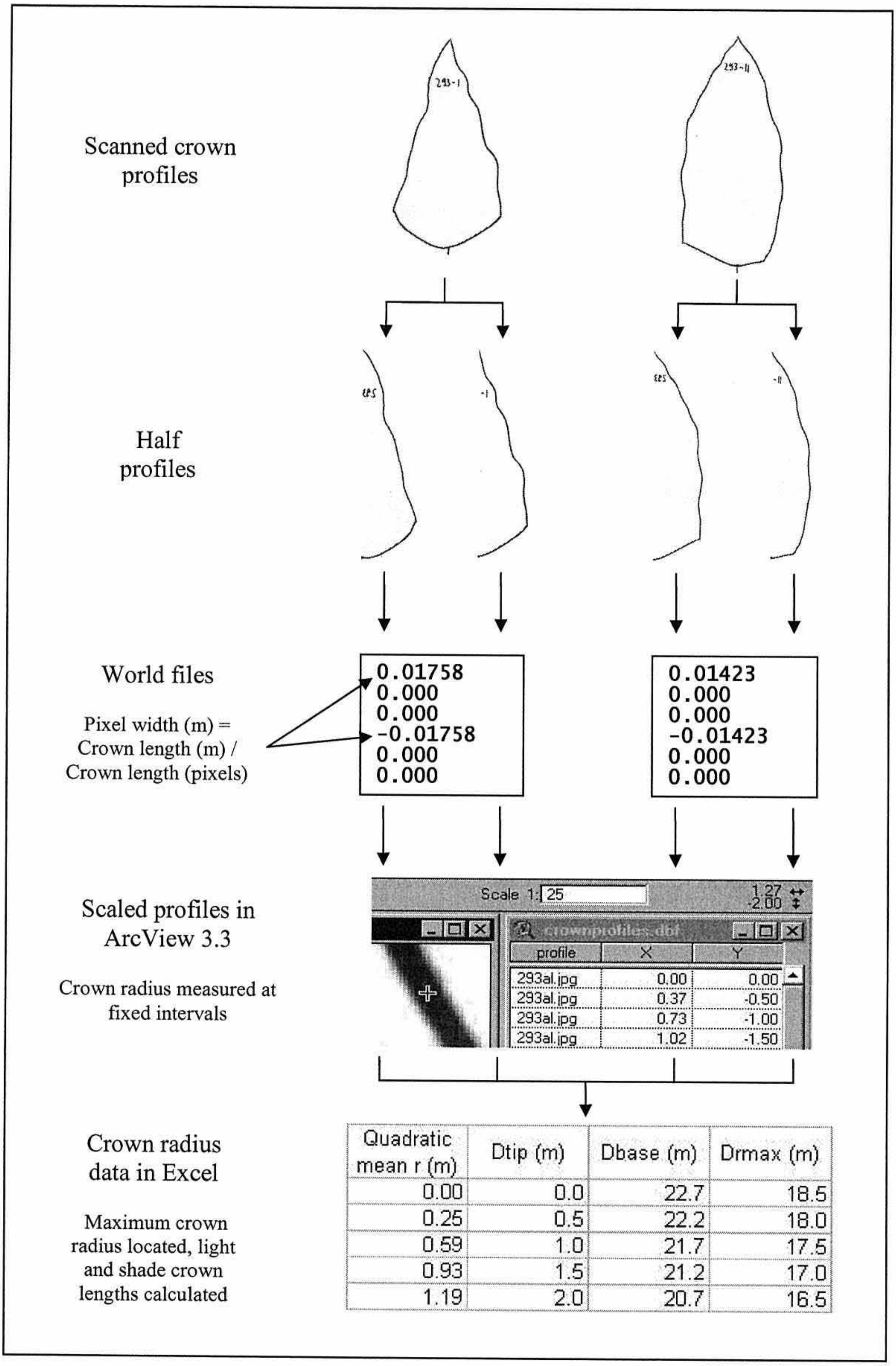
Muth and Bazzaz (2003) described the behaviour of the *RCD* index thus: "[R]elative canopy displacement is a unitless measure, and a value of zero represents a tree with its canopy centered directly above its stem base. For a canopy the shape of a regular polygon, a value greater than one represents a situation in which the canopy is displaced entirely from the stem base. For the majority of forest trees, relative canopy displacement values tend to range between zero and one, indicating that the canopy is displaced but that the stem base is still positioned at some location beneath the canopy."

3.1.4 The "crown window" and crown profile measurements

In addition to the crown survey, crown profile assessments were made in February 2002 for the Sitka spruce in GWY1 using a "crown window" (Hussein *et al.*, 2000), an established method for gathering information on crown shape. Some aspects of the use of the crown window are covered by the crown profile assessment fieldwork protocol in Appendix I. Two orthogonal profiles for each tree were drawn onto transparencies and later digitised with an Epson Expression 1640XL scanner (Epson America Inc.). Total height and height to crown base measurements were made for each profile and averaged for each tree. A single total crown length was calculated for each tree using these mean values. A number of birch trees in the Gwydyr plot were also assessed using the crown window, during September-October 2002. These trees were selected on the basis of visibility rather than following the random crown survey sample, although the sample was intended to follow the *dbh* distribution of the plot as closely as possible. Such is the density of the natural regeneration in GWY1, however, that only 11 trees could be viewed clearly with the crown window.

As in stem profile modelling, the process of modelling a simple, rotationally symmetrical crown profile requires that multiple profiles be reduced to a single, generalised profile for each sample tree. The process for deriving generalised crown profile data from the scanned images is summarised in Fig. 3.5. Scanned profiles were split into half profiles in Paint Shop Pro 7 (Jasc Software Inc.), flipped horizontally if necessary so that the crown tip of each was at the extreme top left corner, and the distance between crown tip and base in pixels was recorded. The pixel width in metres of the half profiles was calculated by dividing crown length in metres by crown length in pixels; these pixel widths were used in "world files" to scale the images in ArcView GIS 3.3 (ESRI Inc.). The world files were also used to set the origin of the co-ordinate system to the top left corner of each image, coinciding with the crown tip, so that co-ordinates read at any point in the image would reflect the true horizontal and vertical distance from the tip. A tool was developed using an Avenue script (reproduced in Appendix II) in ArcView to record the X and Y co-ordinates of the cursor on a mouse click, and this tool was used to collect crown radius data at fixed distances from the crown tip. The interval between measurements varied according to crown length, from 0.1 m for crowns up to 5 m in length to 0.5 m for crowns longer than 20 m. Once radius measurements had been made for all four half profiles for a given tree, the data were imported into Microsoft Excel 2002 (Microsoft Corporation) where quadratic mean radii were calculated for each measurement interval. The maximum crown radius was identified, allowing the separation of light and shade crowns and the calculation of their lengths, and the distances from the crown base and point of maximum crown radius were calculated for each measurement interval in addition to the original measurements of distance from crown tip; this process was automated using a simple Excel macro. The spreadsheet and macro are shown in Appendix II.

Fig. 3.5 Procedure for producing generalised crown profiles.



3.2 Comparison of crown profile assessment methods

Photogrammetric analysis of crown shape was investigated as a potentially more accurate alternative to crown profile assessments using the crown window. Early work on photogrammetry concentrated on establishing appropriate fieldwork techniques and identifying the limitations of the methods in a forestry context. Once a fieldwork protocol was in place, the crown shapes of sample trees were assessed using both photogrammetry and the crown window and the resulting crown data were compared.

3.2.1 The photogrammetry software PhotoModeler Pro 5

The software package PhotoModeler Pro 5 (Eos Systems Inc.) was chosen for photogrammetry analysis work, being relatively inexpensive and having a simple graphical user interface. An earlier version of this software, PhotoModeler Pro 4, was investigated by Riedel (2002) as a non-destructive approach to gathering three-dimensional data on sapling structure. A three-dimensional model in PhotoModeler is based on multiple overlapping photographs of a target object taken from different angles. Features of interest are marked on each photograph, usually as discrete points. These features are then "referenced", whereby marks on multiple photographs are identified as belonging to the same feature, for example the same branch tip appearing in several images. Using this information, PhotoModeler calculates the position of each camera station and referenced feature in three-dimensional space (Eos Systems Inc., 2003).

The successful processing of data to orientate photographs and produce a three-dimensional model depends on certain minimum requirements being met, for example in terms of the number of photographs on which each point appears or the area of each photograph covered by points. Early processing is highly desirable, however, as "auto-drive" referencing can be used to speed the referencing of points on orientated photographs (Eos Systems Inc., 2003, p. 202). When auto-drive is in operation and a point is marked on a single photograph, PhotoModeler can display a line in another photograph upon which the point should lie (the epi-polar line). Once a point has been marked and referenced on at least two photographs, PhotoModeler can drive automatically to the expected position of the point on any other orientated photographs.

This feature of the software greatly increases the efficiency of referencing, so photographs sharing around ten easily identified and widely spaced reference points, which are therefore suitable for early processing, should be sought wherever possible.

A completed model, in which all points of interest have been marked and referenced, can be translated, scaled and rotated. Translation is set by specifying the 3-D co-ordinates of a single point. The model's scale is based on a measured distance between two points. Rotation is set by identifying two of the three axes (X, Y or Z), one of which is chosen to be dominant, by selecting two points on each axis. In the case of crown modelling, the crown tip would be set as the origin of the co-ordinate system (Cartesian co-ordinates 0,0,0) with the dominant Z axis passing vertically through the crown tip and coinciding roughly with the stem of the tree. Tables of co-ordinates can be exported from PhotoModeler for further analysis.

3.2.2 Development of a photogrammetry fieldwork protocol

When tests of photogrammetric techniques began, fieldwork was undertaken largely on a trial and error basis to determine the optimum methods and conditions for the collection of useful data. These efforts were guided by the recommendations in the supporting literature for PhotoModeler, which may be summarised as follows (Eos Systems Inc., 2003, p. 77):

1. The angles between photographs should be as close to 90° as possible.
2. There should be at least three photographs.
3. All important points should appear on at least three photographs.
4. There should be as much overlap between adjacent photographs as possible.
5. Photographs should be taken from both above and below the object, if possible.
6. Many photographs should be taken of the object, but only four should be used initially until more are found to be necessary.
7. The distance should be measured between two visible and clearly delineated points; this distance is used to scale the final model.

For this and all subsequent photogrammetry fieldwork, the best quality digital camera available, a Canon PowerShot G3 (Canon Inc.), was used. Although film cameras may yield images of greater quality than consumer digital cameras, digital photographs may be downloaded immediately rather than undergoing processing and digitising (Eos Systems Inc., 2003, p. 103), minimising the delay between fieldwork and analysis. The PowerShot G3 captures images with a maximum resolution of 2272 by 1704 pixels and has a 4x optical zoom lens with a focal length of 7.2 to 28.8 mm, equivalent to 35 to 140 mm in 35 mm format. PhotoModeler requires that cameras be calibrated at each zoom setting (i.e. focal length) used to acquire photographs in order to account for image distortion; initially, the PowerShot G3 was calibrated only for the minimum focal length of 7.2 mm (wide angle) but was later also calibrated for the maximum focal length of 28.8 mm (telephoto zoom) so that the crowns of large trees could be photographed from greater horizontal distances (see below). Intermediate focal lengths were not calibrated because these could not be selected manually. Both calibrations were carried out as described in the PhotoModeler manual (Eos Systems Inc., 2003, p. 124 *et sqq.*).

Early fieldwork concentrated on Sitka spruce rather than birch, taking advantage of its excurrent growth form (Kozlowski, 1971a) and associated relatively simple crown architecture (Cannell, 1974), as well as its conspicuous buds. Target trees of various sizes and growing in a variety of stand conditions were sought to test the limits of photogrammetric methods in a forestry context (Table 3.3). Ten naturally-regenerated understorey trees, 4.3 to 7.2 m in height, were photographed in plots GWY1, CLG2 and CLG3. Plot CLG3, like plots CLG1 and CLG2, is located in a stand of Sitka spruce planted in 1951, but covers areas where poor drainage has led to windthrow and the subsequent development of dense regeneration in canopy gaps. The six GWY1 trees were photographed first with 45° intervals between camera stations and one ranging rod positioned close by to provide a scale. The CLG2 and CLG3 trees were photographed without ranging rods, but angles between camera stations were reduced from 45° to 30° to simplify branch tip referencing. Models were scaled using the measured distance between the crown tip and the Vertex transponder positioned on the stem; these two points also defined a rough vertical axis. Four of the trees at GWY1 were re-photographed combining elements of both approaches; angles between camera stations were as close to 30° as possible, a measured height was used for scaling and the Vertex transponder and leader defined the vertical axis, but two ranging rods were also positioned near to each tree to provide easily recognised early referencing points. The difficulties encountered during this preliminary fieldwork are described in section 5.1.3.

Table 3.3 Trees and methods used in the development of a photogrammetry fieldwork protocol. An asterisk indicates previously photographed trees re-photographed using different methods.

Plot(s)	Number of trees	Total height, *h*, range (m)	Target camera station interval	Referencing, orientation and scaling aids used
GWY1	6	4.3-7.2	45°	One ranging rod, Vertex
CLG2-3	4	4.6-6.2	30°	Vertex
GWY1	4*	4.3-7.2	30°	Two ranging rods, Vertex
CLG1	5	25.2-27.5	45°	Vertex
CLGS	2	27.6-29.1	30°	Vertex

At the same time as the principles of photogrammetry fieldwork for small understorey trees were being developed, work was underway to establish similar principles for larger canopy trees. One of the limitations of photogrammetry became apparent immediately. All photogrammetry fieldwork was weather dependent, as precipitation could distort images or even damage the camera, and wind, by moving the branch tips between photographs, would inevitably affect accuracy, but canopy trees were particularly badly affected, being fully exposed to the wind. Given the severe wind climate of the British Isles (Quine *et al.*, 1995) this presented a considerable constraint, and assessments often had to be abandoned because of adverse weather conditions.

The first fieldwork tests on overstorey trees took place in CLG1, where the forest canopy is relatively open, with a target camera station interval of 45°. The five sample trees ranged in size from 29.5 to 41.8 cm *dbh* and from 25.2 to 27.5 m in height. For reasons described in section 5.1.3, it proved impossible to model these crowns in PhotoModeler. Further tests on crowns in an even more open canopy were made possible by a seeding felling in a shelterwood strip (designated CLGS) at the eastern edge of the compartment containing plots CLG1-3, with roughly 30 trees retained per hectare. Weather conditions limited fieldwork, and only two sample trees were photographed. These trees were slightly larger than those sampled in CLG1 (tree 1 *dbh* 46.5 cm, *h* 27.6 m, *hcb* 6.5 m; tree 2 *dbh* 46.6 cm, *h* 29.1 m, *hcb* 13.3 m). No referencing aids were used, and the models were to be scaled using measured crown length. Given the difficulties observed in identifying and referencing branch tips in large crowns in CLG1, the target camera station interval was 30°. The majority of photographs were taken at the default wide angle zoom setting relatively close to the target tree, but in a photograph taken from further away using the telephoto zoom the upper whorls were much clearer and more branch detail was visible. The wide angle images did have the one advantage that they consistently showed the entire crown. Despite this, the decision was made to re-photograph the sample trees prioritising viewing distance over the horizontal arrangement of camera stations. Ultimately, however, it was only possible to model portions of these large crowns.

Experiences with canopy trees suggested that, even under exceptionally favourable conditions, photogrammetric modelling of such large crowns was only likely to be possible in the younger whorls, which were less densely foliated and had more easily recognisable branch tips. The comparison of crown profile assessment methods, therefore, had to be undertaken using data only from smaller sample trees, and the fieldwork protocol (Appendix I) was developed accordingly. The recommendations in the protocol were to use three ranging rods evenly spaced around each tree and to take eight photographs with 45° intervals between camera stations. With ranging rods to provide early reference points, 30° camera station intervals were considered unnecessary, but 45° angles still allowed for the ideal 90° separation of pairs of photographs. For small sample trees, ranging rods were thought to provide an adequate scale; this was tested in the field by measuring crown lengths and comparing with modelled values. For orientation of crown models, ranging rods were levelled using a spirit level to provide a vertical axis and held in place with simple tripods.

3.2.3 Individual sample trees

A small number of individual sample trees of both Sitka spruce and birch were selected for the comparison of crown profile assessment methods. These were chosen specifically to offer ideal targets for photogrammetry and the crown window, with as little surrounding vegetation as possible. Three spruce sample trees were located in a third plot in Coed y Brenin, CYB3 (Table 3.4). Plot CYB3 is located in a stand of Sitka spruce planted in 1988, which now has a rather variable stocking density and a substantial component of naturally-regenerated birch; the sample trees were chosen in an area where the planted crop had failed, where visibility was generally good between widely spaced birch regeneration. Crown profile assessments by photogrammetry and using the crown window were undertaken as per the protocol in Appendix I.

Table 3.4 Plot CYB3 summary.

Plot		CYB3
UK grid reference		SH 706 275
Elevation (m asl)		220
Plot area (ha)		0.82
Stocking (stems ≥ 5 cm *dbh* per ha)	Birch	398 (23 %)
	Sitka spruce	1339 (76 %)
	Other species	13 (1 %)
	Total	1750
Basal area (m^2 per ha)	Birch	3 (21 %)
	Sitka spruce	13 (79 %)
	Other species	0 (0 %)
	Total	16

To extend the scope of photogrammetry work to birch, three trees were assessed in plot GWY1. Problems with inclement weather meant that assessments were delayed until mid October when the trees had begun to shed their foliage, and even then conditions had to be accepted which were less than ideal, with heavy cloud cover and no direct sunlight. Isolated naturally-regenerated birch were selected, and some bracken (*Pteridium aquilinum* (L.) Kuhn) clearance was necessary to improve visibility. As with spruce, photogrammetry, crown window and direct crown measurement work was undertaken for all sample trees.

Basic size data for the birch and Sitka spruce individual sample trees are shown in Table 3.5. Note that the birch are larger than the 4 m height threshold suggested in the protocol, as the choice of visible sample trees was limited in GWY1.

Table 3.5 Photogrammetry individual sample tree *dbh* and height data.

Plot	Species	Tree number	*dbh* (cm)	Height (m)
GWY1	Birch	1	5.7	4.6
		2	6.5	5.6
		3	8.1	6.1
CYB3	Sitka spruce	1	3.9	4.0
		2	2.2	3.0
		3	4.3	3.4

3.2.4 Photogrammetry and crown profile measurements

The following procedure for photogrammetric analysis was developed in parallel with the fieldwork protocol, and as such is based entirely on work with Sitka spruce. For a discussion of photogrammetric analysis of birch crowns, see section 4.3.1.

Assuming that photographs were taken in accordance with the fieldwork protocol, analysis proceeded as follows. The terminal bud and three points on each ranging rod (at the lines separating the coloured bands) were marked and referenced on each photograph. If this did not provide enough visible points on all photographs for successful processing, the branch tips of the first whorl were also marked and referenced. After processing, the initial three-dimensional model was checked against field notes to ensure that camera positions had been calculated correctly. The terminal bud was set as the origin of the co-ordinate system, and the ranging rod due south of the leader was used to scale and orientate (vertically along its axis and horizontally from its position to that of the terminal bud) the model. Subsequently, the advanced referencing features of the PhotoModeler software were used to assist the referencing of the remaining branch tips one whorl at a time, with occasional checks of point quality data. Finally, a point was added at the base of a branch in the lowest live whorl so that total crown length, measured vertically from the terminal bud, could be determined. A fully marked and referenced crown image and the associated 3-D model is shown in Fig. 3.6.

As with crown window data, it was necessary to generalise the resulting crown shape to give a simple 2-D profile. For the branch tips in each whorl, arithmetic mean distance from crown tip and quadratic mean crown radius were calculated, effectively giving one average branch tip per whorl. Potential problems with this "mean branch tip per whorl" method are discussed in section 5.1.3.

In addition to producing generalised crown profiles, photographs of the three spruce sample trees were used to recreate crown profile for the previous year. This was accomplished by marking and referencing the previous year's (t-1) leader and branch tips; it should be noted that these points could not be marked as accurately as the current (t) branch tips. The method assumes that there have been no major changes in branch angles after a year of growth. The recreated crown shape was generalised using the mean branch tip per whorl method. By roughly marking a point at the centre of each whorl base, it was also possible to calculate branch lengths for the previous year, as the Euclidean distance between the whorl base and t-1 branch tip, and branch length increment in the last growing season, as the Euclidean distance between t and t-1 branch tips. Absolute increment was divided by t-1 branch length to give relative increment. Fig. 3.7 shows a complete 3-D model of a reconstructed crown, with both t and t-1 branch tips marked.

Fig. 3.6 **PhotoModeler screenshot, showing a fully marked and referenced crown image, co-ordinate table, and the associated 3-D model for sample tree 2 in plot CYB3.**

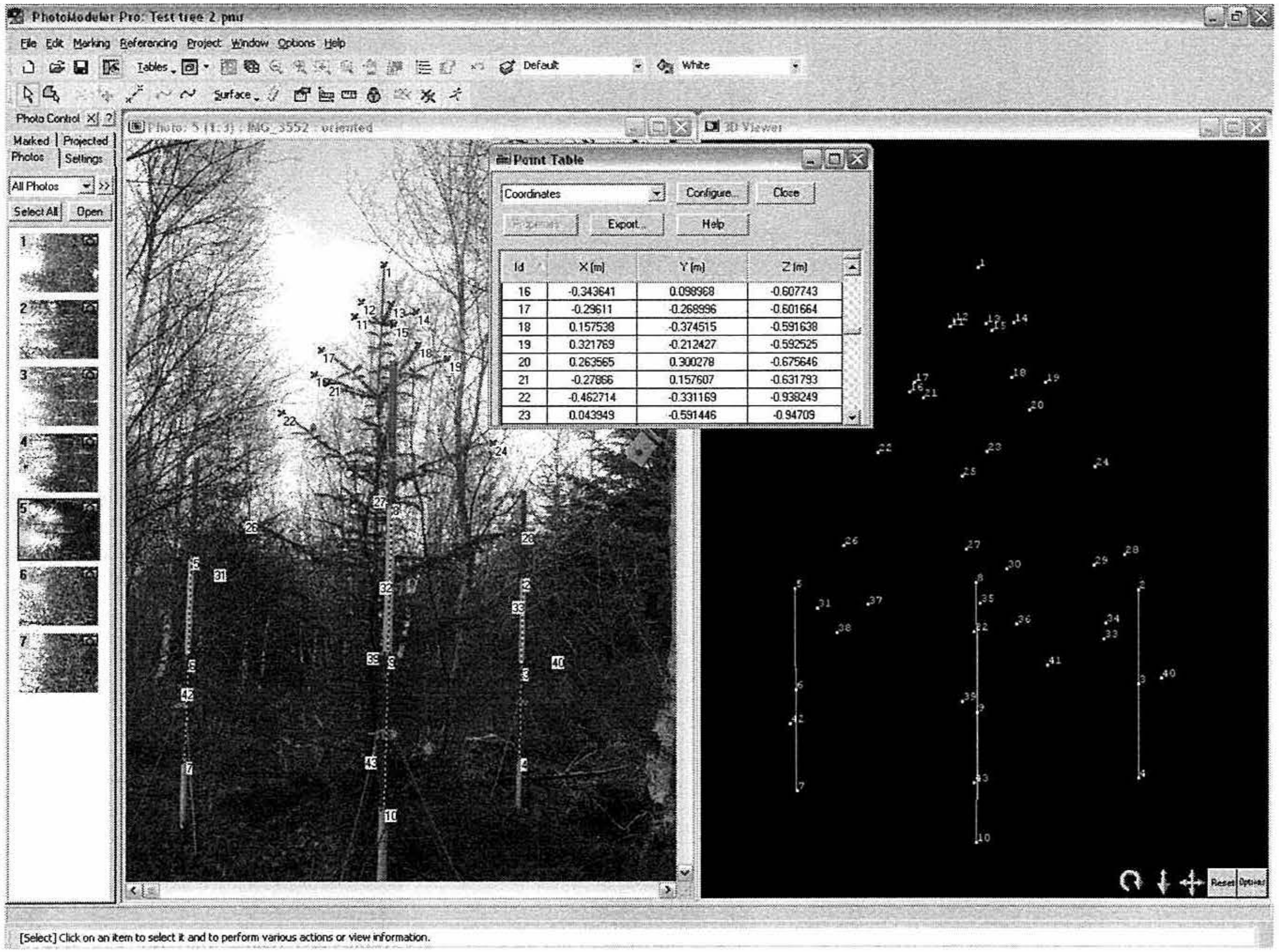
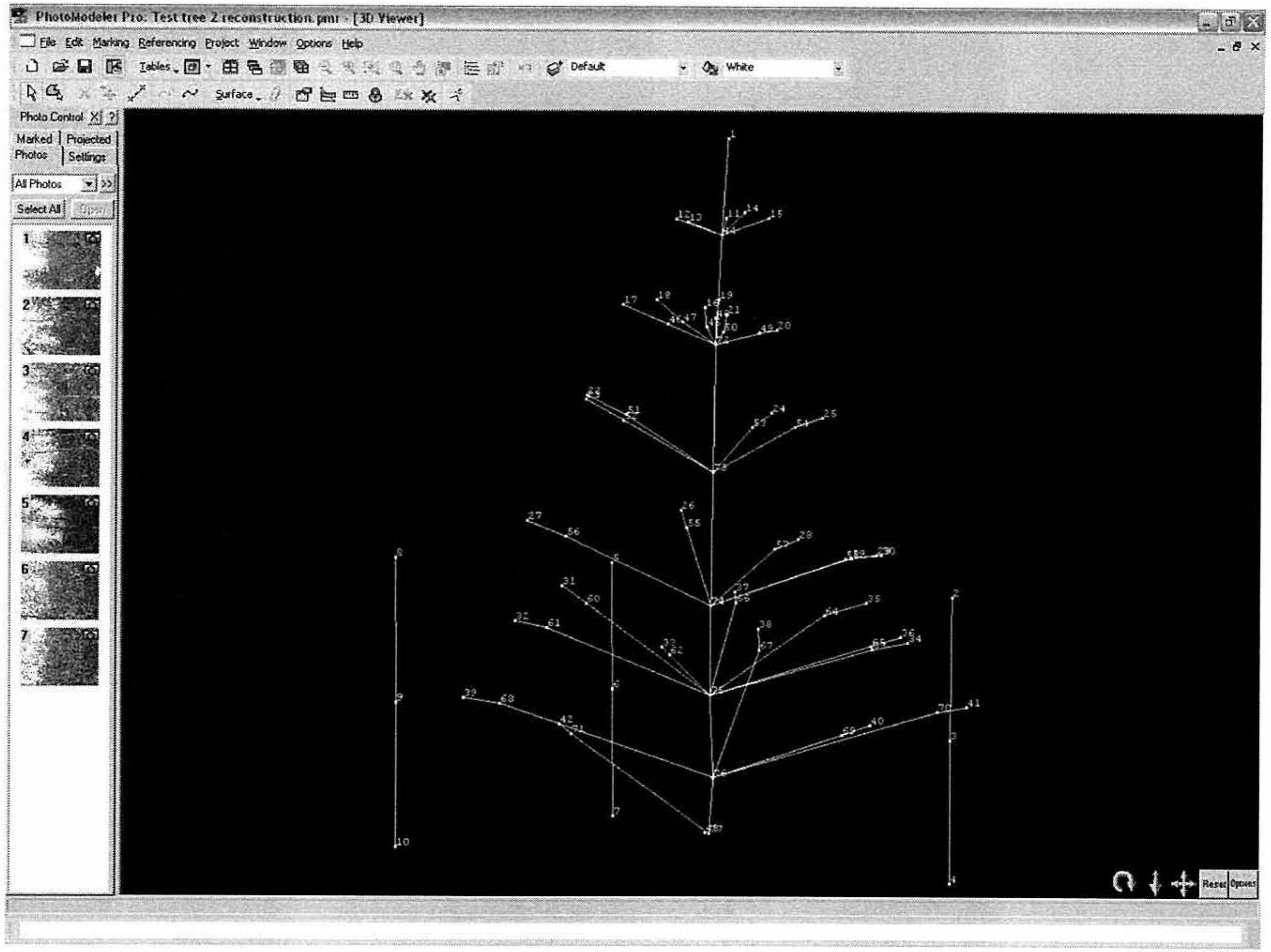


Fig. 3.7 **Crown reconstruction screenshot, showing the complete 3-D model for CYB3 sample tree 2, with lines marking the stem and joining whorl bases, *t*-1 branch tips and *t* branch tips.**



3.2.5 *Analyses*

Analyses for the comparison of methods fell into two categories:

1. Comparisons of gross crown dimension data from direct measurements, the crown window and photogrammetry.
2. Comparisons of crown profile data from the crown window and photogrammetry.

Since there are no "correct" or "true" values for crown dimensions or profiles, these analyses aimed only to establish whether the various methods produced comparable results. In addition, crown reconstruction data were examined to determine whether there were significant changes in crown profile between the time periods t-1 and t, and to explore patterns in branch length increment within the crown.

Crown dimensions from different measurement methods were compared using paired t-tests, with the null hypothesis in each case that the mean difference in values was zero. Since the non-random sampling of trees violated one of the assumptions of the t-test, results should be treated with some caution. Total crown lengths from photogrammetry and direct measurements were compared, as were crown window and photogrammetry light crown lengths; it should be noted that crown window light crown length was given to the nearest 0.1 m but that measurements from photogrammetry depended very much on the locations of mean branch tips. All three methods gave estimates of maximum crown radius, but whereas crown window and photogrammetry maximum radii were based very much on branch tips, direct radius measurements often fell between branch tips and measured the extent of the intervening foliage. Therefore estimates from photogrammetry and the crown window were likely to be noticeably higher.

Two approaches were taken to comparing crown profile data from the crown window and photogrammetry. One was to examine the range and mean of differences in radii measured at distances from the crown tip coinciding with photogrammetry mean branch tips. Because crown window measurements were made at 0.1 m intervals from the crown tip, it was often necessary to interpolate between data points to acquire radius values at the required distances from the crown tip; linear interpolation was considered to be acceptable over such short intervals. The significance of mean differences was tested using the Wilcoxon signed-ranks matched-pairs test; the paired *t*-test was not appropriate because variables were not normally distributed. The second approach was to parameterise light crown profile models (see section 3.3.2) for both crown window and photogrammetry data sets and to use paired *t*-tests to determine whether mean parameter values varied between the two methods (assuming parameter values to be normally distributed). Shade crown profile models were not parameterised because the small sample trees had very short shade crowns.

The latter approach was also used to compare *t* and *t*-1 crown profile data from crown reconstruction. Branch length increment patterns were explored by plotting whorl mean absolute and relative increments against distance from crown tip to whorl base.

3.3 Model selection

As noted previously, simple, deterministic crown models are adequate for the purposes of quantifying competition, and more complex models (e.g. Gill and Biging, 2002) can be avoided, in keeping with the emphasis of the *Tyfiant Coed* growth model on simplicity and parameter parsimony (Pommerening and Wenk, 2002).

3.3.1 Gross crown dimension models

Ideally, the gross crown dimensions of length and maximum radius should be predicted from basic model data such as stem diameter and tree total height. The following maximum crown radius models were chosen for testing on this basis:

(3.5) $$r_{max} = a + b \cdot dbh \qquad \text{(R1)}$$
(various authors, e.g. Hetherington, 1967b)

(3.6) $$r_{max} = a + b \cdot h \qquad \text{(R2)}$$
(Gilmore, 2001)

(3.7) $$r_{max} = a + b \cdot dbh^c \qquad \text{(R3)}$$
(Farr *et al.*, 1989)

(3.8) $$r_{\max} = a + b \cdot dbh + c \cdot dbh^2$$ (R4)
(Gill *et al.*, 2000)

(3.9) $$r_{\max} = e^{a+b \cdot \ln(dbh)}$$ (R5)
(modified from Hasenauer, 1997)

(3.10) $$r_{\max} = e^{a+b \cdot \ln(h)}$$ (R6)
(modified from Hasenauer, 1997)

(3.11) $$r_{\max} = e^{a+b \cdot \ln(dbh)+c \cdot h+d \cdot \ln(h/dbh)}$$ (R7)
(Pretzsch *et al.*, 2002)

where $r_{\max}$ = maximum crown radius (m)
dbh = diameter at breast height (cm)
h = total height (m)
a, b, c, d = regression coefficients
e = base of natural logarithms

The most robust and realistic approach to modelling crown length is to use a crown base increment model (e.g. Hann and Hanus, 2004). Until data are available from remeasurements of the *Tyfiant Coed* permanent sample plots, however, modelling must rely on allometric relationships with other tree dimensions. Total crown length was chosen for modelling because early model tests gave higher parameterisation coefficient of determination (R^2) values than those for height to crown base models. To avoid illogical model behaviour, models were chosen where crown length was constrained to be equal to or less than tree total height; essentially, these models multiply total height by a crown ratio value between zero and unity. Two novel models and two modified from existing models were tested:

(3.12) $$L_{total} = h \cdot e^{-a \cdot \ln(dbh)} \qquad 0 \le a$$ (L1)

(3.13) $$L_{total} = h \cdot e^{-a \cdot \ln(h)} \qquad 0 \le a$$ (L2)

(3.14) $$L_{total} = h \cdot e^{-a \cdot (h/dbh)} \qquad 0 \le a$$ (L3)
(similar to *hcb* model of Nagel *et al.*, 2002)

(3.15) $$L_{total} = h \cdot e^{-(a+b \cdot (h/dbh)+c \cdot dbh)} \qquad 0 \le a,b,c$$ (L4)
(modified from Pretzsch *et al.*, 2002)

where L_{total} = total crown length (m)

Note that, although Pretzsch *et al.* (2002) did not specify any parameter constraints for their *hcb* model, in model L4 all three regression coefficients are constrained so that the exponent is equal to or less than zero for all values of *h* and *dbh*, thereby constraining model outputs between zero and *h*.

Light crown length models were also constrained so that light crown length could not exceed total crown length. The model of relative height of maximum crown radius of MacFarlane *et al.* (2003) was considered too complex (section 2.4.3), even with stand level variables converted to individual tree variables, so four novel models were tested:

(3.16)	$L_{light} = a \cdot L_{total}$	$0 \le a \le 1$	(LL1)
(3.17)	$L_{light} = L_{total} \cdot e^{-a \cdot \ln(dbh)}$	$0 \le a$	(LL2)
(3.18)	$L_{light} = L_{total} \cdot e^{-a \cdot \ln(h)}$	$0 \le a$	(LL3)
(3.19)	$L_{light} = L_{total} \cdot e^{-a \cdot (h/dbh)}$	$0 \le a$	(LL4)

where L_{light} = light crown length (m)

3.3.2 Crown profile models

In addition to gross crown dimension models, four crown profile models were tested, all constrained by maximum crown radius. These models predict crown radius depending on vertical position in the crown, measured from the crown tip, base, or point of maximum radius. One model was intended by its developer for use on light crowns (P1), one was intended for use on shade crowns (P4), and the remaining two could be applied to either light or shade crowns:

(3.20)	$r = r_{max} \cdot (D_{tip} / L_{light})^a$ (modified from Pretzsch, 1992)	$0 < a$	(P1)
(3.21)	$r = -1 \cdot r_{max} \cdot (Dr_{max} / L)^a + r_{max}$ (Seifert, 2002, pers. comm.)	$0 < a$	(P2)
(3.22)	$r = r_{max} \cdot (1 - (Dr_{max} / L)^a)^b$ (Kändler, 1986)	$0 < a, b$	(P3)

(3.23) $r = a \cdot r_{\max} + (1-a) \cdot r_{\max} \cdot (D_{base} / L_{shade})$ $\quad 0 \le a \le 1$ (P4)
(modified from Pretzsch, 1992)

where r = crown radius (m)
D_{tip} = vertical distance from crown tip (m)
D_{base} = vertical distance from crown base (m)
$Dr_{\max}$ = vertical distance from height of maximum crown radius (m)
L_{shade} = shade crown length (m)
L = light or shade crown length (m)

Model P1 is based on a power relationship between D_{tip} and r (Pretzsch, 1992), modified so that maximum crown radius is achieved when vertical distance from the crown tip is equal to light crown length. The models of Seifert (2002) and Kändler (1986) were chosen as one- and two-parameter variations on the equation for an ellipse (see section 2.4.3); Kändler's (1986) model was chosen in preference to the very similar model of MacFarlane *et al.* (2003) because of the extra flexibility afforded by two separate regression coefficients. In model P4, modified from the simple linear relationship between D_{base} and r used by Pretzsch (1992), the parameter a gives the width of the crown base as a proportion of $r_{\max}$, with r increasing linearly between the crown base and the point of maximum radius.

3.4 Model testing

The model testing process involved two main stages, namely parameterisation and statistical validation. Data sets were split randomly to provide separate sets for each stage of modelling. Maximum crown radius and total crown length models were tested by plot and for the combined crown survey data set for each species. Data set sizes are shown in Table 3.6; note that the random separation into parameterisation and validation data sets was not the same for combined data sets as for individual plots.

For light crown length and crown profile modelling based on crown window data from plot GWY1, the same division of spruce data into parameterisation and validation sets was used. Of the 11 birch sampled for crown shape, six were randomly assigned to the parameterisation data set and five were assigned to the validation data set.

Table 3.6 Crown model parameterisation and validation data set sizes.

Species	Plot	Data set size (number of trees)	
		Parameterisation	Validation
Birch	CYB1	13	12
	CYB2	13	12
	GWY1	13	12
	All plots	38	37
Sitka spruce	CLG1	25	25
	CLG2	13	12
	CYB1	13	12
	CYB2	13	12
	GWY1	15	14
	All plots	77	77

3.4.1 Model parameterisation

Gross crown dimension model parameterisations were carried out using the non-linear regression facility of SPSS 11.5 (SPPS Inc.). Where parameter values were constrained (see formulæ in section 3.3.1) sequential quadratic programming was used for parameter estimation, and where they were unconstrained the Levenberg-Marquardt algorithm was used.

Two approaches were taken to crown profile model parameterisation. In one approach, each model was parameterised simultaneously for all light or shade crowns, as appropriate, of each species, by combining crown profile, maximum crown radius and crown length data for all trees in one data file. As all parameter values were constrained, sequential quadratic programming was used throughout. These parameterisations resulted in one parameter value per model per species.

In the alternative approach, each model was parameterised separately for the light or shade crown of each tree. These parameterisations resulted in several parameter values per model per species. Before the models could be applied to trees for which they had not been parameterised, sub-models were required to account for the tree to tree variation in parameter values. Various methods are available for calculating appropriate parameter values (Hussein, 2001). Realistic model behaviour can only be guaranteed if generated parameter values are correctly constrained (as specified above), so in this study sub-model forms were chosen specifically to match the necessary parameter constraints. Sub-models were tested using a range of stem, crown and spatial independent variables (Table 3.7); spatial variables are described in detail in section 3.5. Eight forms were tested for models P1-3, where parameter values must be greater than zero:

(3.24)	$y = e^{a \cdot x}$	
(3.25)	$y = e^{a/x}$	
(3.26)	$y = e^{a \cdot (x-b)}$	
(3.27)	$y = e^{a \cdot ((1/x)-b)}$	
(3.28)	$y = x^{a}$	
(3.29)	$y = a \cdot x^{b}$	$0 < a$
(3.30)	$y = (a + x)^{b}$	$0 < a$
(3.31)	$y = a + b \cdot x$	$0 \leq a, b$

where y = dependent variable (crown profile model parameter value)
x = independent variable (see Table 3.7)

All of these model forms assume positive values of x. Where the independent variable could assume a value of zero (as with most spatial variables; see Table 3.7) equations 3.25 and 3.27 used $(x+1)$ in place of x (to avoid division by zero), and equations 3.28 and 3.29 were not tested (to avoid raising zero to the power zero or a negative number; equation 3.30 avoided this problem by adding a positive number to x).

Table 3.7 Crown profile sub-modelling independent variables.

Independent variable		Used in light crown models?	Used in shade crown models?	May equal zero?
dbh	Diameter at breast height (cm)	Yes	Yes	No
h	Total height (m)	Yes	Yes	No
h/dbh	Height:diameter ratio	Yes	Yes	No
hcb	Height to crown base (m)	Yes	Yes	No
L_{total}	Total crown length (m)	Yes	Yes	No
L_{light}	Light crown length (m)	Yes	No	No
L_{shade}	Shade crown length (m)	No	Yes	No
$r_{\max}$	Maximum crown radius (m)	Yes	Yes	No
$L_{total}/r_{\max}$	Crown slenderness ratio	Yes	Yes	No
$L_{light}/r_{\max}$	Light crown slenderness ratio	Yes	No	No
$L_{shade}/r_{\max}$	Shade crown slenderness ratio	No	Yes	No
L_{total}/h	Crown ratio	Yes	Yes	No
L_{light}/L_{total}	Light crown ratio	Yes	No	No
L_{shade}/L_{total}	Shade crown ratio	No	Yes	No
$HDist$	Horizontal distance to nearest neighbour (m)	Yes	Yes	No
W	Uniform angle index	Yes	Yes	Yes
M	Species mingling index	Yes	Yes	Yes
$Udbh$	Diameter dominance index	Yes	Yes	Yes
Uh	Height dominance index	Yes	Yes	Yes
$N_{0.01}$	Stocking of 0.01 ha circular plot (stems ha^{-1})	Yes	Yes	Yes
$N_{0.02}$	Stocking of 0.02 ha circular plot (stems ha^{-1})	Yes	Yes	Yes
$BA_{0.01}$	Basal area of 0.01 ha circular plot (m^2 ha^{-1})	Yes	Yes	Yes
$BA_{0.02}$	Basal area of 0.02 ha circular plot (m^2 ha^{-1})	Yes	Yes	Yes
BAL	Basal area of larger trees (m^2 ha^{-1})	Yes	Yes	Yes
$Hg_{0.01}$	Hegyi competition index for 0.01 ha circular plot	Yes	Yes	Yes
$Hg_{0.02}$	Hegyi competition index for 0.02 ha circular plot	Yes	Yes	Yes
N_{HA}	Number of competitors selected by height angle (stems)	Yes	Yes	Yes
BA_{HA}	Basal area of competitors selected by height angle (m^2)	Yes	Yes	Yes
BAL_{HA}	Basal area of larger competitors selected by height angle (m^2)	Yes	Yes	Yes
Hg_{HA}	Hegyi index for competitors selected by height angle	Yes	Yes	Yes

Three sub-model forms were tested for model P4, where the a parameter must have a value between zero and unity:

(3.32) $$y = e^{-a \cdot x} \qquad 0 \leq a$$

(3.33) $$y = e^{-a/x} \qquad 0 \leq a$$

(3.34) $$y = (a + x)^{-b} \qquad 1 \leq a,\ 0 \leq b$$

As with equations 3.25 and 3.27, (x+1) was used in equation 3.33 in place of x where the independent variable could assume a value of zero, in order to avoid division by zero.

3.4.2 Model validation

Crown dimension model validations, comparing observed and predicted values of maximum crown radius, total crown length and light crown length, were carried out in Excel. Similar validations were carried out for values of crown radius predicted using crown profile models. Model bias, precision, accuracy and efficiency (Pretzsch and Ďurský, 2001; Pretzsch *et al.*, 2002; Gadow *et al.*, 2003) were calculated as follows:

(3.35) $$Mean\ bias = \frac{\sum_{i=1}^{n}(x_i - X_i)}{n}$$

(3.36) $$Relative\ bias\ (\%) = \frac{Mean\ bias}{\overline{X}} \cdot 100$$

(3.37) $$Precision = \sqrt{\frac{\sum_{i=1}^{n}((x_i - X_i) - Mean\ bias)^2}{n-1}}$$

(3.38) $$Relative\ precision\ (\%) = \frac{Precision}{\overline{X}} \cdot 100$$

(3.39) $$Relative\ accuracy\ (\%) = \frac{\sqrt{Precision^2 + Mean\ bias^2}}{\overline{X}} \cdot 100$$

$$(3.40) \qquad Efficiency = 1 - \frac{\sum_{i=1}^{n}(x_i - X_i)^2}{\sum_{i=1}^{n}(X_i - \overline{X})^2}$$

where $\overline{X}$ = mean observation ($r_{\max}$, L_{total}, L_{light} or r)
X_i = ith observation ($r_{\max}$, L_{total}, L_{light} or r)
x_i = ith prediction ($r_{\max}$, L_{total}, L_{light} or r)
n = number of observations

The concepts of bias and precision are explained by Gadow and Hui (1999, p. 185); accuracy combines these two concepts, so that a precise and unbiased prediction is considered accurate. Smaller values reflect superior relative bias, precision or accuracy, while better efficiency values approach unity (Gadow *et al.*, 2003).

In addition to this statistical evaluation, crown dimension model outputs for each parameterisation were plotted for a range of tree sizes (*dbh* 5-30 cm for birch and 5-80 cm for spruce, the approximate ranges of parameterisation data) and considered in terms of biological realism. Where tree total height was required as a model input, values were calculated using a height curve (Prodan, 1951) parameterised with data from all trees of the relevant species in each plot:

$$(3.41) \qquad h = 1.3 + \frac{dbh^2}{a + b \cdot dbh + c \cdot dbh^2}$$

Where total crown length was required as an input for light crown length models, values were calculated using model L2.

Statistical validations were carried out twice for each tree in the crown profile model validation data sets; once using parameter values fixed by simultaneous parameterisation and once using values derived through sub-modelling.

3.5 Spatial variables

Spatial variables were calculated for inclusion in the crown profile sub-modelling process (section 3.4.1, Table 3.7) and in order to explore relationships with gross crown dimensions, potentially yielding improved models. Variables were chosen to be relatively simple and readily calculated from available plot inventory data. Calculations of structural indices, measures of local stand density and competition indices were made in Excel using a macro. Plot inventory data on tree number, species, X, Y and Z co-ordinates, *dbh* and total height were entered. Horizontal distances between each subject tree and all other trees in the plot were calculated from X and Y co-ordinates using Pythagoras' theorem so that nearest neighbours could be identified. The spreadsheet and macro are explained in detail in Appendix II.

3.5.1 Structural indices

Four structural indices (Pommerening, 2002) were calculated for each sample tree. The uniform angle index, *W* (Gadow and Hui, 2002; Pommerening, 2002; Aguirre *et al.*, 2003), which characterises the regularity of the spatial arrangement of trees, was calculated for each structural group of four, comprising the reference tree and its four nearest neighbours:

(3.42) $$W_i = \frac{1}{n}\sum_{j=1}^{n} v_j \qquad 0 \le W_i \le 1$$

where	W	= uniform angle index
	i	= reference tree
	j	= neighbour tree
	n	= number of neighbours (4)
	v_j	= 1, $\alpha_j < \alpha_0$; 0, otherwise
	α_j	= smallest angle between neighbour j and next neighbour clockwise
	α_0	= reference angle (72°)

Hui and Gadow (2002) explained the derivation of the reference angle. With a structural group of four, the uniform angle index can assume five values (Gadow and Hui, 2002; Table 3.8).

Table 3.8 Values of the uniform angle index.

W_i	Description	Category
0.00	None of the angles α_j is smaller than α_0	Very regular
0.25	One of the angles α_j is smaller than α_0	Regular
0.50	Two of the angles α_j are smaller than α_0	Random
0.75	Three of the angles α_j are smaller than α_0	Irregular
1.00	All four of the angles α_j are smaller than α_0	Very irregular

Species mingling, *M* (Gadow and Hui, 2002; Pommerening, 2002; Aguirre *et al.*, 2003), was also calculated for each structural group of four:

(3.43) $$M_i = \frac{1}{n}\sum_{j=1}^{n} v_j \qquad 0 \le M_i \le 1$$

where M = species mingling
v_j = 1, reference tree *i* and neighbour *j* are of different species; 0, otherwise

Note that this definition follows Gadow and Hui (2002) and Pommerening (2002) in that mingling is the proportion of the reference tree's nearest neighbours that do not belong to the same species; greater values of the index indicate that the reference tree is mingled with more trees of different species. With four neighbours, five values are possible (Gadow and Hui, 2002; Table 3.9).

Table 3.9 Values of the species mingling index.

M_i	Description	Category
0.00	All four neighbours belong to the same species	Zero mingling
0.25	Three neighbours belong to the same species	Weak mingling
0.50	Two neighbours belong to the same species	Moderate mingling
0.75	Three neighbours belong to different species	High mingling
1.00	All four neighbours belong to different species	Maximum mingling

Two indices describing dimension dominance, *U* (Gadow and Hui, 2002; Aguirre *et al.*, 2003), were calculated, one based on stem diameter at breast height, *Udbh*, and the other based on tree total height and elevation, *Uh*:

$$(3.44) \qquad Udbh_i = \frac{1}{n}\sum_{j=1}^{n} v_j \qquad 0 \le Udbh_i \le 1$$

where *Udbh* = *dbh* dominance
v_j = 1, $dbh_j < dbh_i$; 0, otherwise

$$(3.45) \qquad Uh_i = \frac{1}{n}\sum_{j=1}^{n} v_j \qquad 0 \le Uh_i \le 1$$

where *Uh* = height dominance
v_j = 1, $(h_j + Z_j) < (h_i + Z_i)$; 0, otherwise
Z = elevation (Z co-ordinate (m); see section 3.1.1)

Note that these definitions follow Aguirre *et al.* (2003) rather than Gadow and Hui (2002) in that dominance is the proportion of neighbour trees smaller than the reference tree; greater value of the index indicate that the reference tree is more dominant within the structural group. Height dominance, *Uh*, incorporates the elevation of each tree in addition to its height, reflecting the influence of topography on vertical canopy stratification and dominance. Dominance indices can assume five values (modified from Gadow and Hui, 2002; Table 3.10).

Table 3.10 Values of the dimension dominance index.

U_i	Description	Category
0.00	All four neighbours are larger than the reference tree	Very suppressed
0.25	Three neighbours are larger than the reference tree	Moderately suppressed
0.50	Two neighbours are larger than the reference tree	Co-dominant
0.75	Three neighbours are smaller than the reference tree	Dominant
1.00	All four neighbours are smaller than the reference tree	Strongly dominant

3.5.2 *Measures of local stand density*

Two simple measures of local stand density were calculated for circular sample plots centred on each subject tree, namely the stocking (*N*, stems per hectare) and basal area (*BA*, m^2 per hectare) of trees over 5 cm *dbh* (excluding the subject tree). Sample plot areas were 0.01 ha (all plots) and 0.02 ha (Clocaenog and Gwydyr plots). 0.02 ha plots were not used in CYB1 and CYB2 because the plot radius of 7.98 m exceeded the width of the buffer zone for sample tree selection (6 m).

3.5.3 *Competition indices*

Two simple competition indices were calculated for each subject tree, one distance-independent and one distance-dependent. The distance-independent index was the basal area of larger trees (*BAL*, m^2 per hectare) as calculated by Schröder and Gadow (1999), multiplying stand basal area by the basal area percentile of the subject tree. The distance-dependent index was that of Hegyi (1974) as calculated by Gadow and Hui (1999):

$$(3.46) \qquad Hg_i = \sum_{j=1}^{n} \left(\frac{dbh_j}{dbh_i} \cdot \frac{1}{HDist_{ij}} \right)$$

where
Hg = Hegyi distance-dependent competition index
dbh_i = *dbh* of subject tree *i* (cm)
dbh_j = *dbh* of competitor *j* (cm)
$HDist_{ij}$ = horizontal distance between subject tree *i* and competitor *j* (m)
n = number of competitors

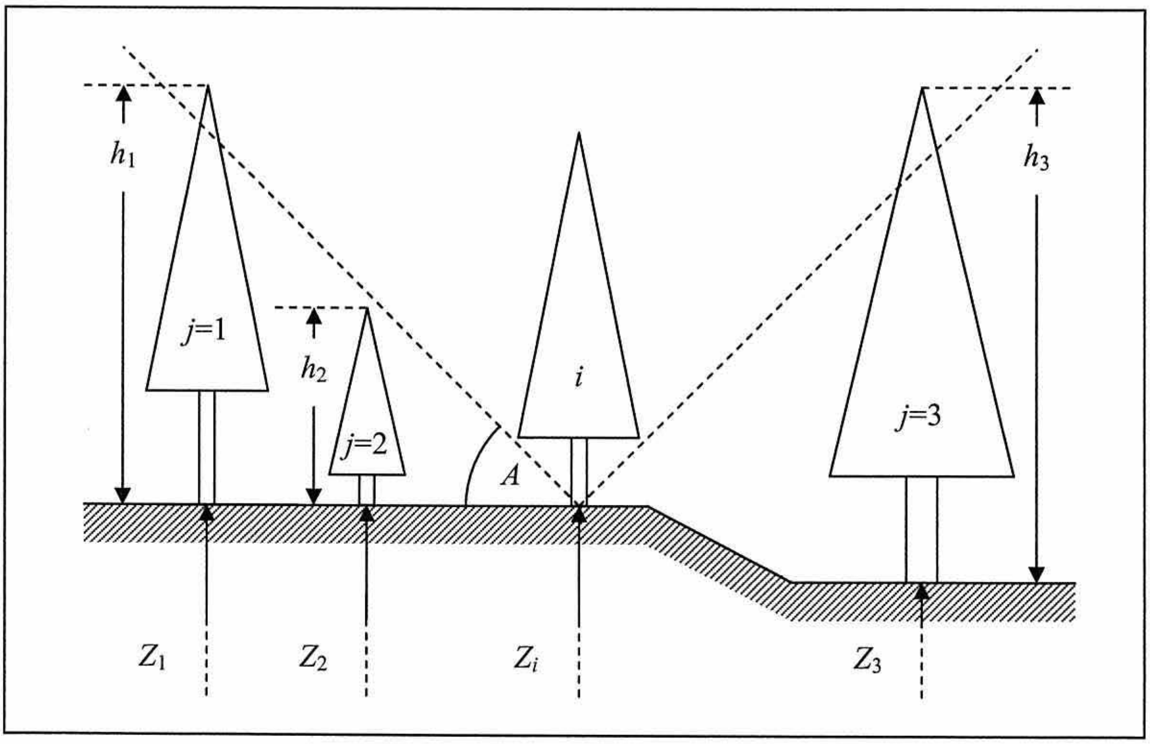
The Hegyi index was calculated for the same 0.01 ha and 0.02 ha circular plots as the measures of stand density, assuming that every tree within each plot was a competitor. In addition, more sophisticated means of identifying competitors were trialled based on the work of Biging and Dobbertin (1992), specifically their "height angle" method. Trees were identified as competitors if they grew above a line extending from the base of the subject tree at a specified angle (*A*) from the horizontal (Fig. 3.8). In Excel, neighbours were selected as competitors when:

(3.47) $$h_j + Z_j \geq \tan(A) \cdot HDist_{ij} + Z_i$$

where
A = height angle (°)
h_j = total height of neighbour j (m)
$HDist_{ij}$ = horizontal distance between subject tree i and neighbour j (m)
Z_i = elevation (Z co-ordinate) of subject tree i (m)
Z_j = elevation (Z co-ordinate) of neighbour j (m)

A height angle of 75° was chosen; taking into account the maximum tree height observed in each plot, this avoided selecting competitors further away from each subject tree than the width of the buffer zone for sample tree selection. Competitors identified for each subject tree were used to calculate the number of competitors (N_{HA}), the basal area of competitors (BA_{HA}, m²), the basal area of larger competitors (BAL_{HA}, m², calculated by summing the basal areas of competitors of larger *dbh* than the subject tree) and the Hegyi competition index (Hg_{HA}).

Fig. 3.8 Height angle competitor selection. In this example, with a height angle of *A*, neighbour trees *j*=1 and *j*=3 are identified as the competitors of subject tree *i*. *h* and *Z* are tree total height (m) and elevation (Z co-ordinate, m) respectively.



3.5.4 *Analyses*

In addition to their use in parameter sub-models for crown profile models (see section 3.4.1), spatial variables were used in attempts to improve the predictive power of crown dimension models. Relationships between gross crown dimensions and spatial variables were first examined through non-parametric (Spearman's) correlation analyses, by species and plot, and for the combined data set for each species. Alternative maximum crown radius models were produced by stepwise linear regression, using *dbh*, height and spatial variables as independent variables. The development of properly constrained crown length models was based on four basic model forms:

(3.48) $$L_{total} = h \cdot e^{-a \cdot x} \qquad 0 \leq a$$

(3.49) $$L_{total} = h \cdot e^{-a/x} \qquad 0 \leq a$$

(3.50) $$L_{total} = h \cdot e^{-(a \cdot (h/dbh) + b \cdot x)} \qquad 0 \leq a, b$$

(3.51) $$L_{total} = h \cdot e^{-(a \cdot (h/dbh) + b/x)} \qquad 0 \leq a, b$$

where x = independent variable

Only spatial variables were used as independent variables. For equations 3.49 and 3.51, (x+1) was used in place of x in most cases, since all spatial variables except horizontal distance to nearest neighbour could assume values of zero. Equations 3.50 and 3.51 were based on model L3. Crown length models based on spatial variables may perform unrealistically if used to predict the development of crown length over time, potentially resulting in decreases in height to crown base as spatial variables change. This problem, which is also an issue with models L1-4 to a lesser extent, is discussed in section 5.3. Such models may, however, be acceptable when predictions are required for a single time step only.

For each parameterisation data set, the five crown length models with the highest R^2 values and crown radius models with parameterisation R^2 values greater than those of models R1-7 underwent statistical validation using the separate validation data sets.

4 RESULTS

4.1 Crown survey data summaries

4.1.1 Diameter and height distributions

Fig. 4.1 shows diameter distributions for birch and spruce crown sample trees. These may be compared with whole plot distributions (Fig. 3.3) to determine the status of the sample trees. The birch sample trees, being naturally regenerated and either understorey (GWY1) or relatively suppressed canopy trees (CYB1, CYB2), are in the smallest classes. The spruce samples in the largely monocultural plots CLG1 and CLG2 follow the overall plot distributions closely. As spruce form the majority of the canopy in CYB1 and CYB2, the samples have bell-shaped distributions at the upper end of the range of sizes observed for the plots. The Gwydyr spruce sample shows the clear dichotomy between planted overstorey and naturally-regenerated understorey, with no intermediate tree sizes. Note that because of the delay between plot inventory and crown survey, many of the larger trees have advanced to the next diameter class.

Height distributions for the birch and spruce samples are shown in Fig. 4.2. The birch samples cover the same limited range of height classes as they do diameter classes, but whereas the diameter distributions are skewed the height distributions approach normality. Compared with plot inventory height distributions (Fig. 3.4), the Coed y Brenin birch samples approximately cover the centres of the height distributions (the smaller height classes being made up by species such as willow) while the Gwydyr sample is at the lower end of the plot distribution. The spruce sample height distributions follow the sample diameter distributions relatively closely. The height distribution for the CLG1 sample is more or less normal, as is that for CLG2 with the addition of a small peak in the 5 m class. The CYB1 sample height distribution does not appear to approximate normality as closely as the *dbh* distribution, but is more irregularly spread between the 7.5 and 17.5 m classes, covering the middle to upper range of height classes for the plot. The CYB2 sample distribution covers a slightly narrower range and shows a very even spread of sample trees across the height classes 12.5 to 17.5 m. As with the diameter distribution, the GWY1 sample height distribution shows two distinct cohorts, with canopy tree heights approximating normality and the understorey distribution rather skewed.

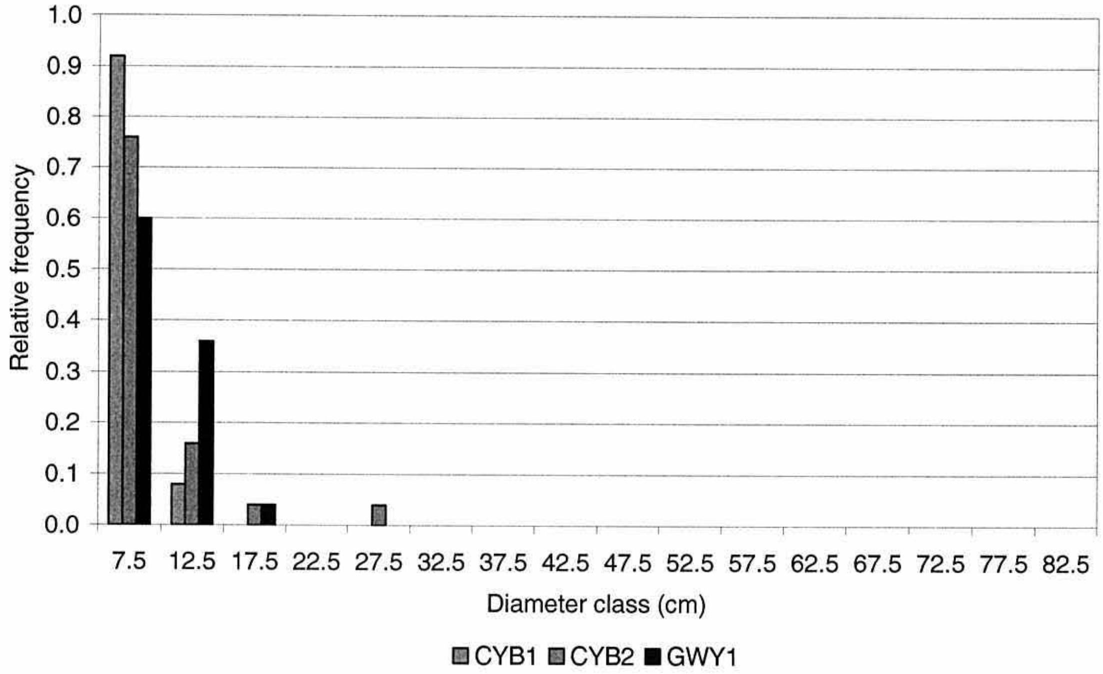
Table 4.1 shows permanent sample plot and crown survey sample data ranges by species. As samples were random and excluded buffer zones in each plot, they did not always capture the full range of tree sizes for each species; the CYB2 Sitka spruce sample, for example, failed by a considerable margin to capture both the upper and lower extremes of *dbh* and height in the plot. In some cases (CYB2 birch *dbh*, GWY1 spruce *dbh* and height), tree growth between plot establishment and the crown survey gave rise to sample maxima greater than plot maxima.

Table 4.1 Birch and Sitka spruce plot and crown survey sample data ranges.

		Diameter at breast height, *dbh* (cm)		Total height, *h* (m)	
Data set		Mean	Range	Mean	Range
CYB1 birch	Plot	8.0	5.0-17.6	10.4	4.8-15.7
	Sample	7.3	5.1-13.3	10.0	6.7-13.4
CYB2 birch	Plot	9.1	5.0-26.1	10.4	5.0-15.4
	Sample	8.8	5.1-26.2	10.3	6.6-15.1
GWY1 birch	Plot	7.9	5.0-18.6	6.6	4.0-12.7
	Sample	9.1	5.2-15.0	7.0	4.0-11.0
CLG1 Sitka spruce	Plot	35.8	20.4-55.5	26.7	17.2-34.2
	Sample	37.2	23.1-55.0	26.9	20.5-32.3
CLG2 Sitka spruce	Plot	35.8	5.1-59.2	24.5	3.6-32.6
	Sample	34.2	6.8-56.0	23.6	4.7-29.3
CYB1 Sitka spruce	Plot	18.6	5.0-36.0	13.2	3.4-21.6
	Sample	17.3	7.2-25.3	12.7	6.6-17.3
CYB2 Sitka spruce	Plot	18.0	5.6-39.7	13.6	3.4-22.7
	Sample	20.7	11.6-32.1	15.0	11.1-18.7
GWY1 Sitka spruce	Plot	31.5	5.0-79.9	15.7	2.6-31.2
	Sample	38.4	5.9-83.0	19.3	4.0-36.0

Fig. 4.1 Crown survey sample diameter distributions, showing the proportion of stems in each sample occurring in 5 cm *dbh* classes for (a) birch and (b) Sitka spruce.

(a)



(b)

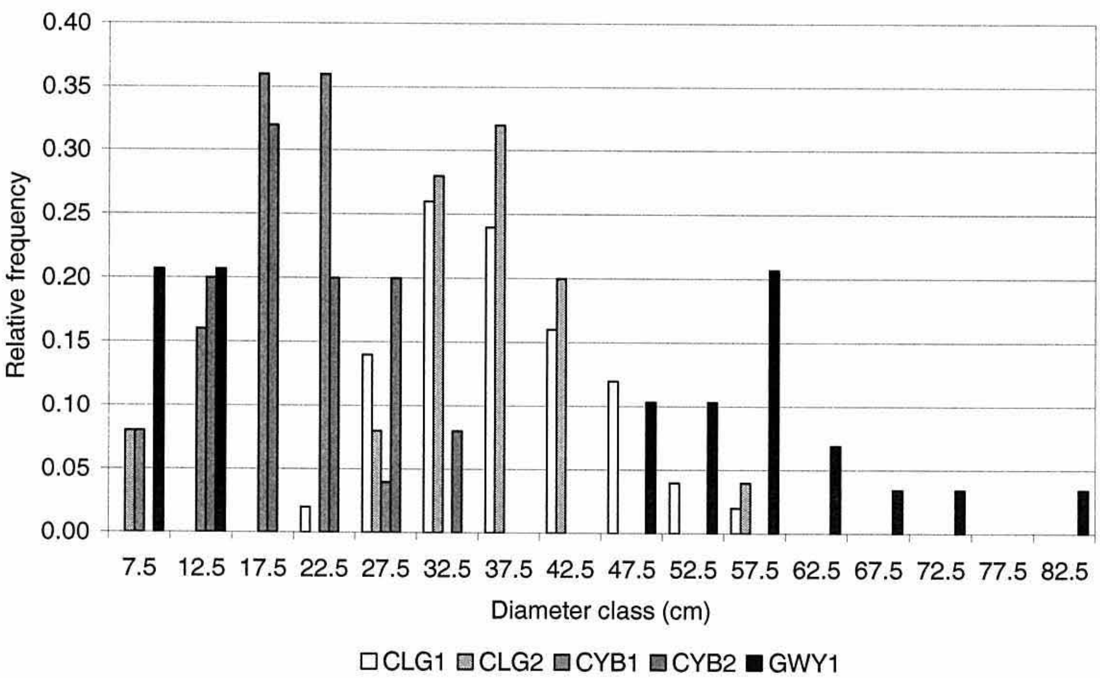
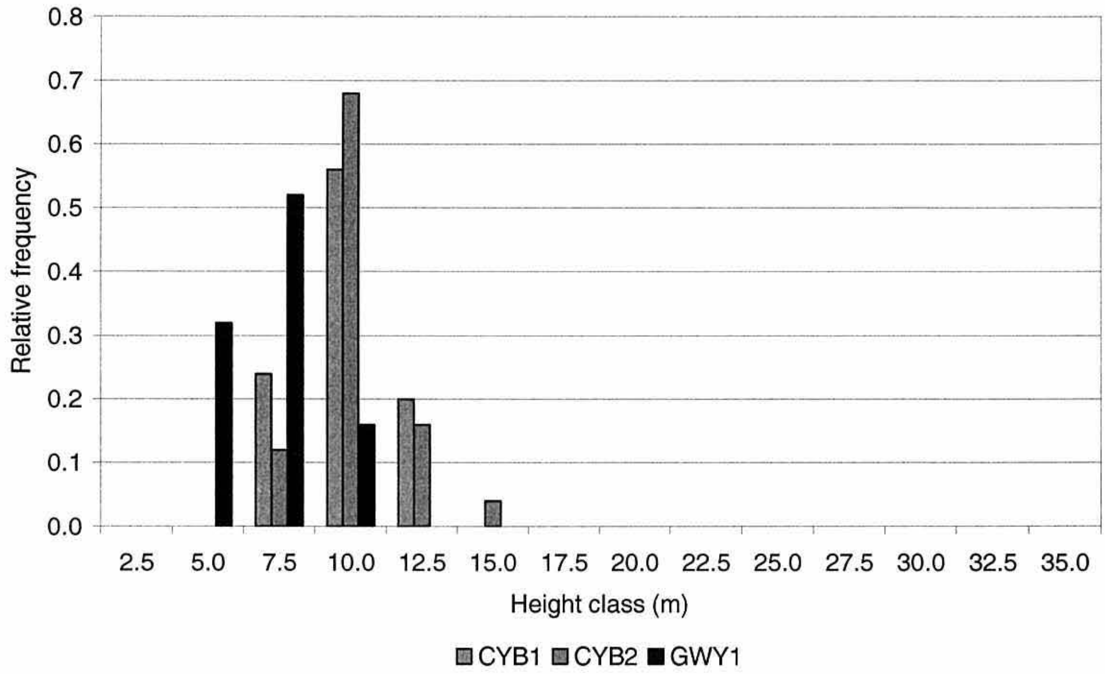
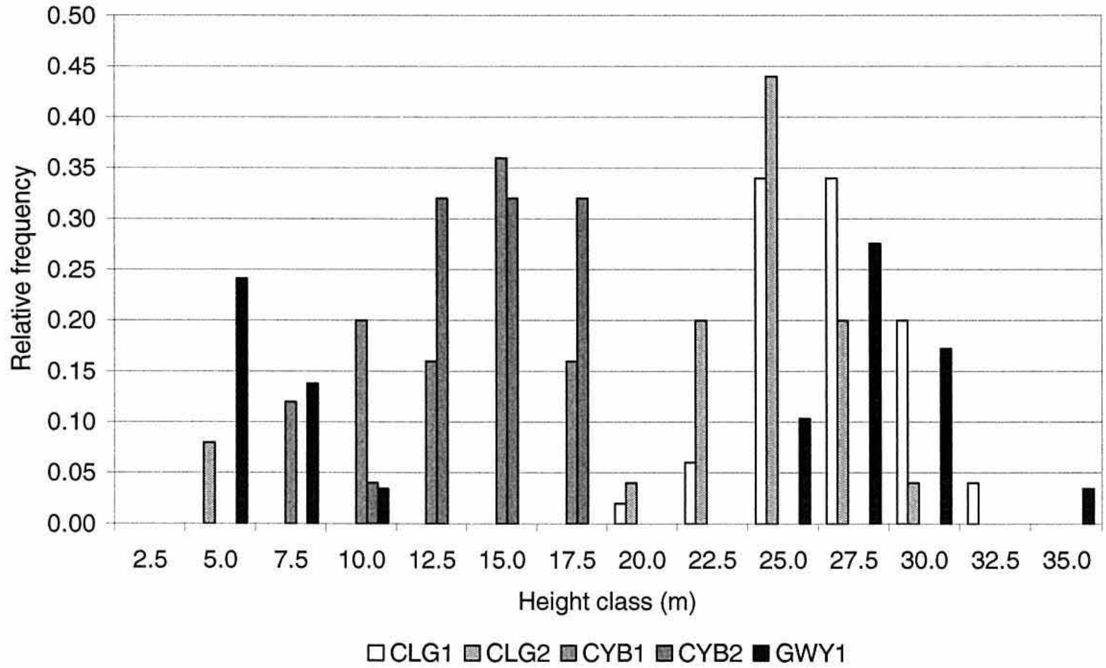


Fig. 4.2 **Crown survey sample height distributions, showing the proportion of stems in each sample occurring in 2.5 m total height classes for (a) birch and (b) Sitka spruce.**

(a)



(b)



4.1.2 *Crown dimensions*

The means and ranges of dimensions measured in the crown survey are given in Table 4.2 for birch and Table 4.3 for spruce. The birch samples for CYB1 and CYB2 are similar, except that CYB1 has an exceptionally low minimum crown length of 0.8 m. Maximum crown radius can be as low as 0.43 or 0.66 m in CYB1 and CYB2 respectively. Such narrow crowns result from physical constriction by the more dominant canopy spruce. Birch crown measurements at Coed y Brenin were complicated by the fact that, post-thinning, the heavily suppressed birch tended to droop or lean significantly. This affected total height and height to crown base measurements, but had a more profound effect on crown radii measured from the breast height point when the crown was no longer overhead. No such problems were encountered in GWY1, where the only difficulty was poor visibility in dense regeneration. Crown displacement and uniformity in crown shape are quantified below.

Table 4.2 Birch crown survey summary data. For details of measurements and calculations see Appendix I and section 3.1.3.

	Maximum crown radius, $r_{\max}$ (m)		Height to crown base, *hcb* (m)		Total crown length, L_{total} (m)	
Data set	Mean	Range	Mean	Range	Mean	Range
CYB1	0.94	0.43-1.91	5.3	2.6-7.9	4.6	0.8-10.5
CYB2	1.10	0.66-1.76	5.1	2.5-7.1	5.2	2.8-9.4
GWY1	1.86	1.26-2.64	1.9	0.8-3.1	5.1	2.0-9.6

Only problems with visibility affected spruce crown measurements, and these were not severe. Results for CLG1 and CLG2 are broadly similar. The small naturally-regenerated trees in the CLG2 sample depress the minimum *hcb* and L_{total} values but not $r_{\max}$. Results for CYB1 and CYB2 are also similar, although CYB2 shows a wider range of crown radii and a narrower range of heights to crown base; the former may suggest greater horizontal structural heterogeneity in this plot. The GWY1 sample displays the greatest range of crown widths and lengths, encompassing both regeneration trees just above the 5 cm *dbh* threshold and exceptionally large canopy trees up to 83 cm *dbh*.

Table 4.3 Sitka spruce crown survey summary data. For details of measurements and calculations see Appendix I and section 3.1.3.

	Maximum crown radius, r_{max} (m)		Height to crown base, *hcb* (m)		Total crown length, L_{total} (m)	
Data set	Mean	Range	Mean	Range	Mean	Range
CLG1	2.52	1.35-3.78	13.2	8.4-18.1	13.7	7.2-20.8
CLG2	2.48	1.46-3.70	10.0	0.4-15.9	13.6	4.3-22.1
CYB1	1.43	0.94-1.92	4.5	1.1-8.2	8.2	4.6-14.2
CYB2	1.47	0.58-2.51	4.6	2.2-7.1	10.3	4.9-14.8
GWY1	2.84	1.48-4.50	6.4	0.1-14.8	12.9	3.3-29.0

As noted above, such was the asymmetry of the crowns of many of the suppressed birch in the Coed y Brenin plots that the crown did not extend outwards from the stem in some directions; indeed the crowns of seven trees (78, 114, 140 and 240 in CYB1; 68, 584 and 591 in CYB2) had only one measurable radius. In some cases this was due to the irregular outline of the crown resulting from differential growth of branches around the main stem. In other cases, trees with high height:diameter ratios leaned heavily when supporting trees were removed during thinning so that the crown was displaced relative to the stem.

Averages and ranges of coefficients of variation of crown radius measurements are shown in Table 4.4. The Coed y Brenin birch have by far the most irregular crowns, with mean coefficients of variation in excess of one and maximum values approaching three. Mean values for spruce are in all cases closer to zero than those for birch; the Coed y Brenin samples have the highest mean and maximum coefficients of variation of crown radius, suggesting that the trees in these relatively densely stocked stands face greater competition for space and light than in the Clocaenog and Gwydyr plots.

Averages and ranges of relative canopy displacement values (see section 3.1.3) for crown survey sample trees are given in Table 4.5. As with coefficients of variation of crown radius, Coed y Brenin birch and spruce show the highest mean and maximum values for their species, with the birch showing by far the highest values overall. The mean values greater than one suggest that the majority of trees in these data sets have crowns completely displaced from their stems.

The simple maximum crown radius and crown profile models typically employed in competition indices assume that crowns are rotationally symmetrical. The results of these analyses of uniformity in crown shape and relative canopy displacement suggest that the birch crowns at Coed y Brenin are not approximately rotationally symmetrical, and consequently that modelling results for these trees may be poor.

Table 4.4 Birch and Sitka spruce crown survey uniformity in crown shape.

	Coefficient of variation of crown radius	
Data set	Mean	Range
CYB1 birch	1.34	0.13-2.83
CYB2 birch	1.25	0.24-2.83
GWY1 birch	0.43	0.11-1.05
CLG1 Sitka spruce	0.32	0.13-0.63
CLG2 Sitka spruce	0.30	0.12-0.57
CYB1 Sitka spruce	0.42	0.13-0.84
CYB2 Sitka spruce	0.40	0.10-1.44
GWY1 Sitka spruce	0.28	0.11-0.67

Table 4.5 Birch and Sitka spruce crown survey relative canopy displacement.

	Relative canopy displacement	
Data set	Mean	Range
CYB1 birch	1.23	0.10-2.48
CYB2 birch	1.16	0.16-2.47
GWY1 birch	0.38	0.05-1.22
CLG1 Sitka spruce	0.28	0.06-0.67
CLG2 Sitka spruce	0.25	0.06-0.63
CYB1 Sitka spruce	0.41	0.05-1.02
CYB2 Sitka spruce	0.37	0.10-1.64
GWY1 Sitka spruce	0.23	0.03-0.65

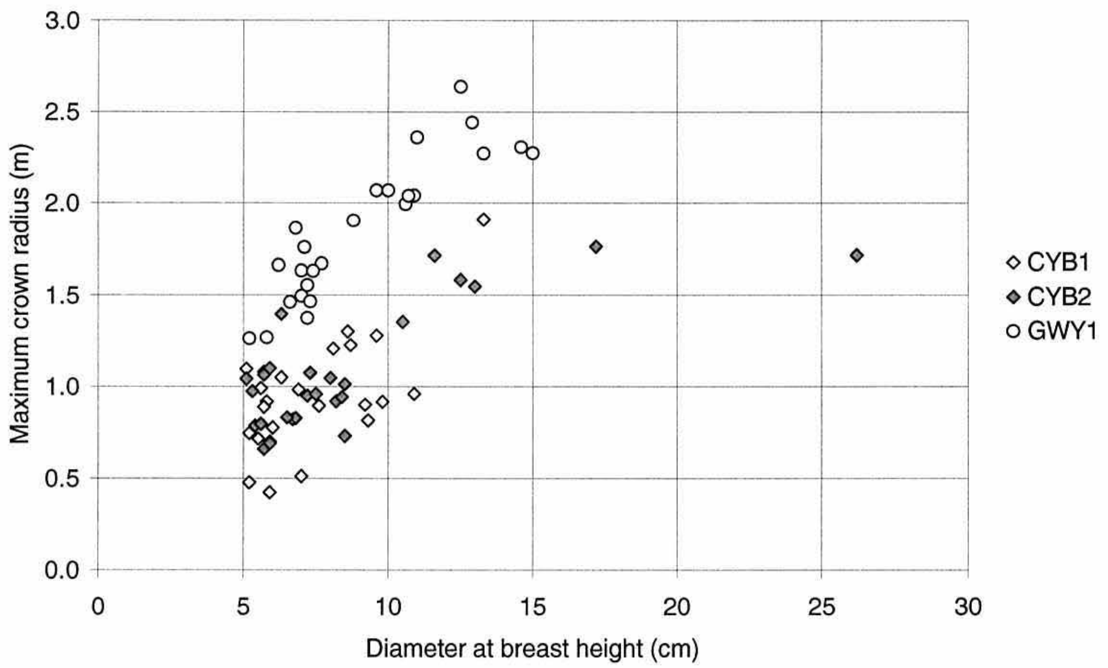
4.1.3 *Relationships between stem and crown dimensions*

Fig. 4.3 plots stem diameter against maximum crown radius by species and plot. For birch (Fig. 4.3(a)), the apparent relationships between *dbh* and crown radius in the Coed y Brenin plots are largely determined by the larger trees above around 10 cm *dbh*; below this *dbh* it is difficult to discern any trends. There is some evidence of a positive linear relationship in both samples, particularly if one ignores the effect of the outlier above 25 cm *dbh* in CYB2. A positive linear relationship is clearly evident in the GWY1 sample. Similar trends are apparent in the data for Sitka spruce (Fig. 4.3(b)); the majority of these data, indeed, seem to conform to single, relatively strong linear relationship. The exceptions are the naturally-regenerated trees in CLG2 and GWY1 which form a separate, parallel trend at low diameters; these trees have wider crowns at a given *dbh*, presumably because they are growing with less horizontal constriction than the planted canopy trees, or because they are responding to shading by increasing lateral branch extension at the expense of height growth.

Total height is plotted against total crown length in Fig. 4.4. Positive, roughly linear relationships are evident for birch (Fig. 4.4(a)); the Coed y Brenin samples seem to follow the same trend line while birch in GWY1 have longer crowns at a given height, presumably because lower stocking (Table 3.1) allows the retention of live branches lower down the stem. Fig. 4.4(b) seems to show three distinct trends for spruce, all positive and apparently linear; one is formed by the natural regeneration in CLG2 and GWY1, one by the CYB1 and CYB2 samples, and one by the mature trees of CLG1, CLG2 and GWY1. The loss of lower live branches in the last group, which now has the shortest crowns for a given total height, must reflect higher past stocking densities, since the canopy trees in these plots are now relatively widely spaced.

Fig. 4.3 **Maximum crown radius plotted against stem diameter by plot for (a) birch and (b) Sitka spruce crown survey sample trees.**

(a)



(b)

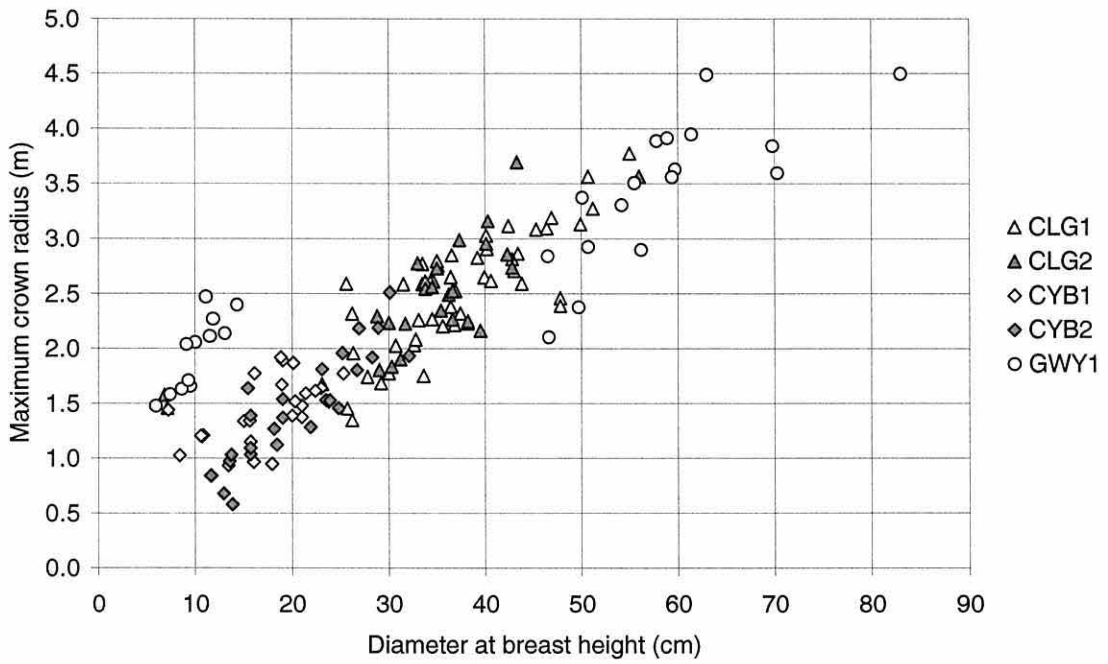
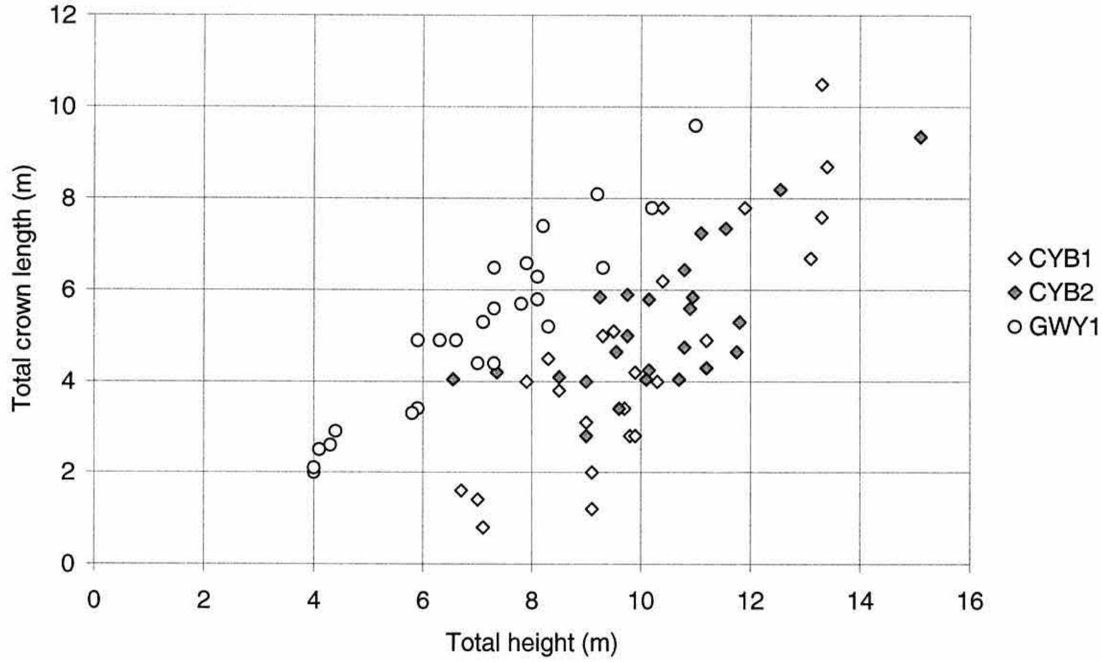
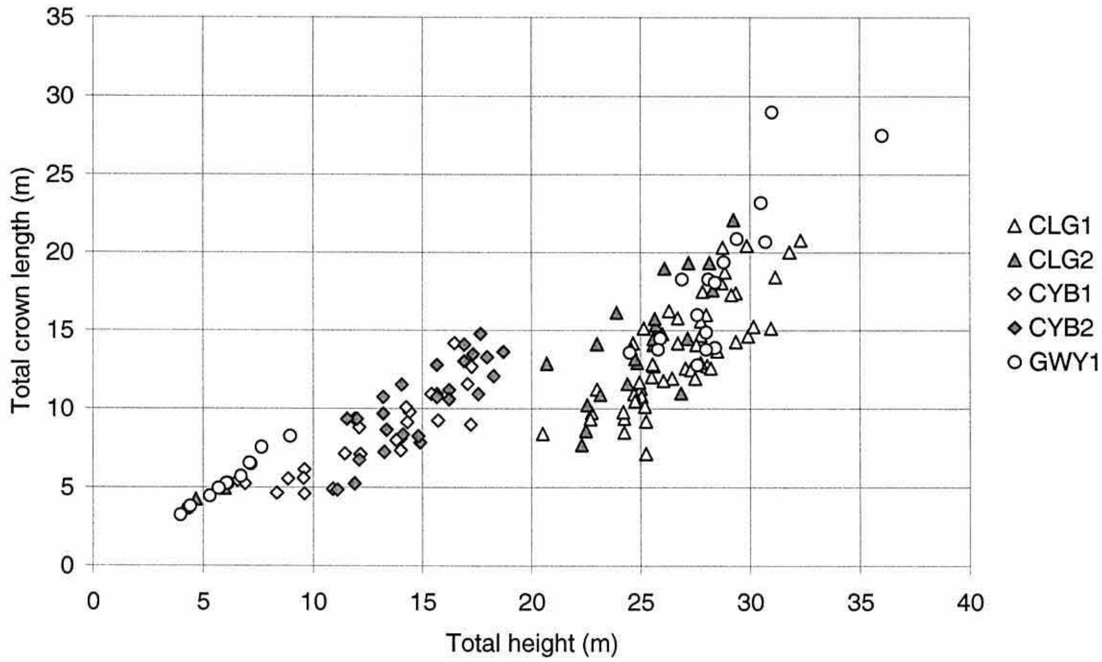


Fig. 4.4 Total crown length plotted against total height by plot for (a) birch and (b) Sitka spruce crown survey sample trees.

(a)



(b)



The strength of the linear relationships observed in these charts may be established by non-parametric correlation analysis[4]. Results of analyses for the birch samples are shown in Table 4.6. Stem diameter is significantly positively correlated with maximum crown radius and total crown length for all data sets. Total height is consistently significantly positively correlated with total crown length. Correlations with height to crown base are variable in both magnitude and direction; this is true also for the spruce sample data (Table 4.7). For spruce, both *dbh* and height are significantly positively correlated with crown radius and total length for all data sets.

Table 4.6 Birch stem and crown dimension non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees).

Stem dimension	Data set	Maximum crown radius, r_{max} (m)	Height to crown base, *hcb* (m)	Total crown length, L_{total} (m)
Diameter at breast height, *dbh* (cm)	CYB1 ($n = 25$)	0.411*	-0.261	0.764**
	CYB2 ($n = 25$)	0.564**	0.226	0.468*
	GWY1 ($n = 25$)	0.875**	-0.014	0.667**
	All plots ($n = 75$)	0.623**	-0.234*	0.639**
Total height, *h* (m)	CYB1 ($n = 25$)	0.289	-0.073	0.807**
	CYB2 ($n = 25$)	0.246	0.377	0.663**
	GWY1 ($n = 25$)	0.640**	0.035	0.925**
	All plots ($n = 75$)	-0.271*	0.557**	0.563**

[4] Parametric analysis would be inappropriate because variables are not normally distributed in all cases.

Table 4.7 Sitka spruce stem and crown dimension non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees).

Stem dimension	Data set	Maximum crown radius, r_{max} (m)	Height to crown base, *hcb* (m)	Total crown length, L_{total} (m)
Diameter at breast height, *dbh* (cm)	CLG1 ($n = 50$)	0.762**	-0.164	0.728**
	CLG2 ($n = 25$)	0.768**	0.052	0.596**
	CYB1 ($n = 25$)	0.604**	0.372	0.783**
	CYB2 ($n = 25$)	0.889**	-0.041	0.790**
	GWY1 ($n = 29$)	0.949**	0.635**	0.908**
	All plots ($n = 154$)	0.862**	0.671**	0.865**
Total height, *h* (m)	CLG1 ($n = 50$)	0.517**	-0.113	0.827**
	CLG2 ($n = 25$)	0.497*	-0.013	0.820**
	CYB1 ($n = 25$)	0.579**	0.510**	0.883**
	CYB2 ($n = 25$)	0.686**	0.067	0.808**
	GWY1 ($n = 29$)	0.809**	0.597**	0.965**
	All plots ($n = 154$)	0.778**	0.726**	0.876**

4.2 Crown window data summaries

4.2.1 Diameter and height distributions

There was an interval of two years between crown window profile assessments and direct crown measurements for the spruce sample trees in GWY1 (see sections 3.1.3 and 3.1.4); as a result, there are some differences in the stem diameter and height distributions from the two assessments. Diameter distributions for the spruce and birch crown window samples are shown in Fig. 4.5. The spruce distribution is very similar to that for the crown survey sample (Fig. 4.1(b)), except that by the time of the crown survey several trees had advanced to the next diameter class. Although the birch crown window assessments and crown survey sampled different trees, they covered the same range of dimensions, from 7.5 to 17.5 cm (Fig. 4.1(a)).

Fig. 4.5 Crown window sample diameter distributions, showing the proportion of stems in GWY1 birch and Sitka spruce samples occurring in 5 cm *dbh* classes.

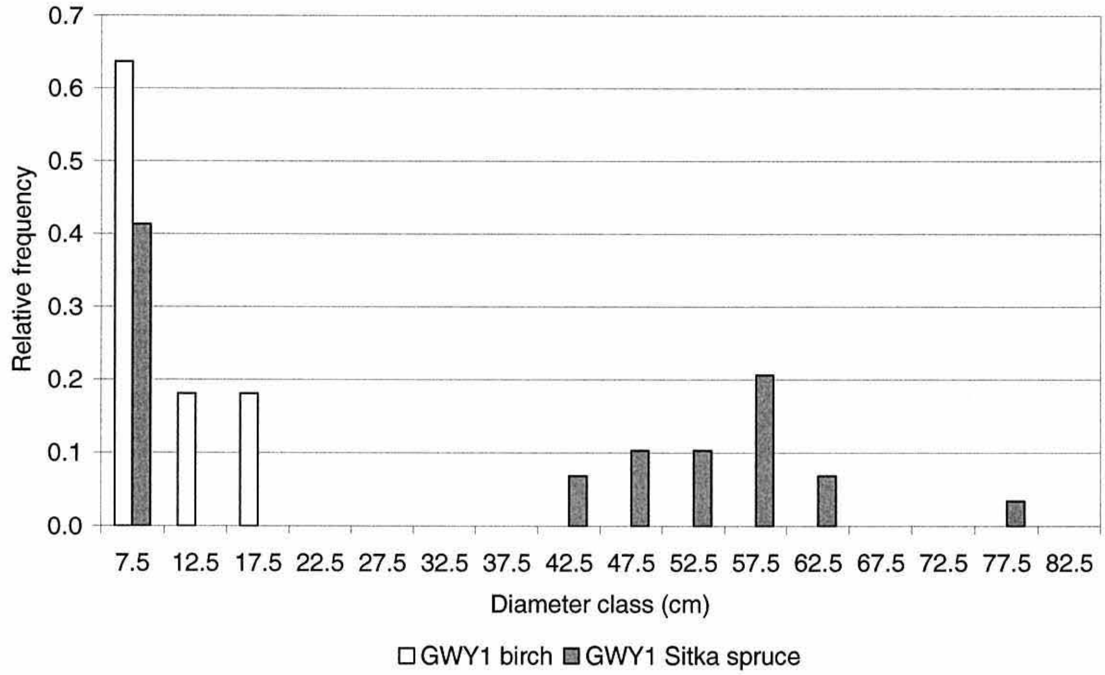
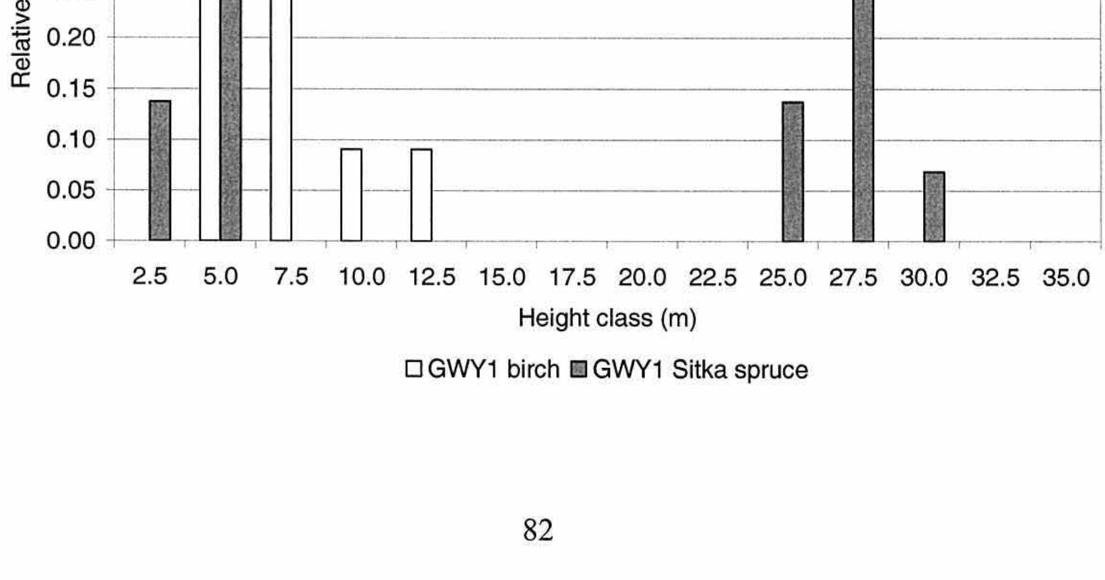


Fig. 4.6 Crown window sample height distributions, showing the proportion of stems in GWY1 birch and Sitka spruce samples occurring in 2.5 m total height classes.



Height distributions are shown in Fig. 4.6. Again, the birch distribution is similar to that for the crown survey sample (Fig. 4.2(a)), except that the crown window sample includes one slightly larger tree in the 12.5 m class. The spruce distribution is also broadly similar to that shown in Fig. 4.2(b). The naturally-regenerated understorey trees have grown relatively swiftly, most having advanced at least one size class by the time of the crown survey. Less height growth is evident in the overstorey trees, although one tree has moved up two size classes from 30.0 to 35.0 m between the two assessments.

4.2.2 *Crown dimensions*

Measured heights to crown base and derived total crown lengths, and light crown lengths and maximum crown radii from generalised crown profiles (see section 3.1.4) are summarised in Table 4.8. For the birch, the ranges of values for *hcb* and L_{total} are close to those for the crown survey (Table 4.2), and even maximum crown radius data are similar despite the different measurement methods (see comments on differences in $r_{\max}$ in section 3.2.5). For spruce, the crown window produces far more variable estimates of crown radius than direct measurements (Table 4.3). There are also some quite substantial differences in height to crown base between the two assessments; minimum, mean and maximum values are all lower in the later crown survey, which unfortunately suggests some sort of systematic measurement error or bias in identifying the crown base, as the definition in use does not allow *hcb* to decrease with time (Appendix I).

Table 4.8 Crown window sample summary data. For details of measurements and calculations see Appendix I and section 3.1.3.

	Maximum crown radius, $r_{\max}$ (m)		Height to crown base, *hcb* (m)		Total crown length, L_{total} (m)		Light crown length, L_{light} (m)	
Data set	Mean	Range	Mean	Range	Mean	Range	Mean	Range
GWY1 birch	2.02	1.00-3.45	1.9	0.5-4.0	5.3	2.8-9.7	3.3	1.8-7.4
GWY1 spruce	2.91	0.79-5.30	7.4	0.4-16.5	10.6	2.2-22.7	7.9	1.4-18.5

4.2.3 *Relationships between stem and crown dimensions*

Maximum crown radius seems to exhibit a relatively strong linear relationship with *dbh* in the birch sample (Fig. 4.7). This relationship is less obvious in spruce, and is certainly less strong than that observed for directly measured crown radius (Fig. 4.3(b)). The greater variability of crown profile radii may be due to the fact that they are averages of measurements in only four directions rather than eight direct measurements.

Relationships between total height and light crown length (Fig. 4.8) for both species are similar to those between total height and total crown length (Fig. 4.4); this is because light crown length shows such a close relationship with total crown length (Fig. 4.9).

Fig. 4.7 Crown window maximum crown radius plotted against stem diameter for GWY1 birch and Sitka spruce crown window sample trees.

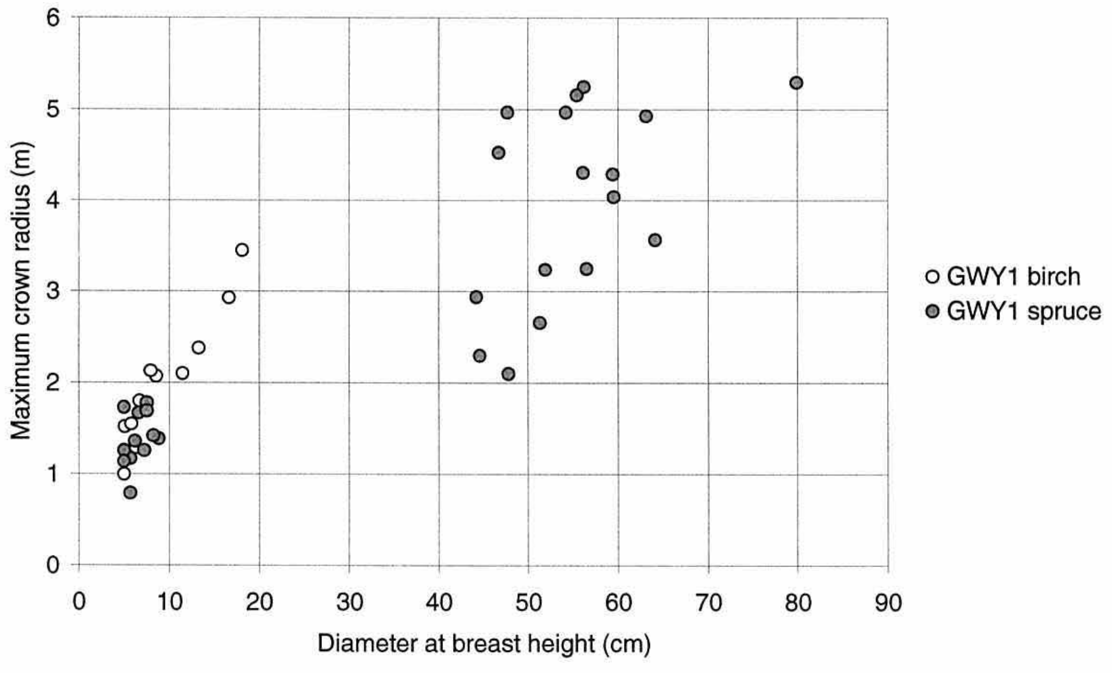


Fig. 4.8 Light crown length plotted against total height for GWY1 birch and Sitka spruce crown window sample trees.

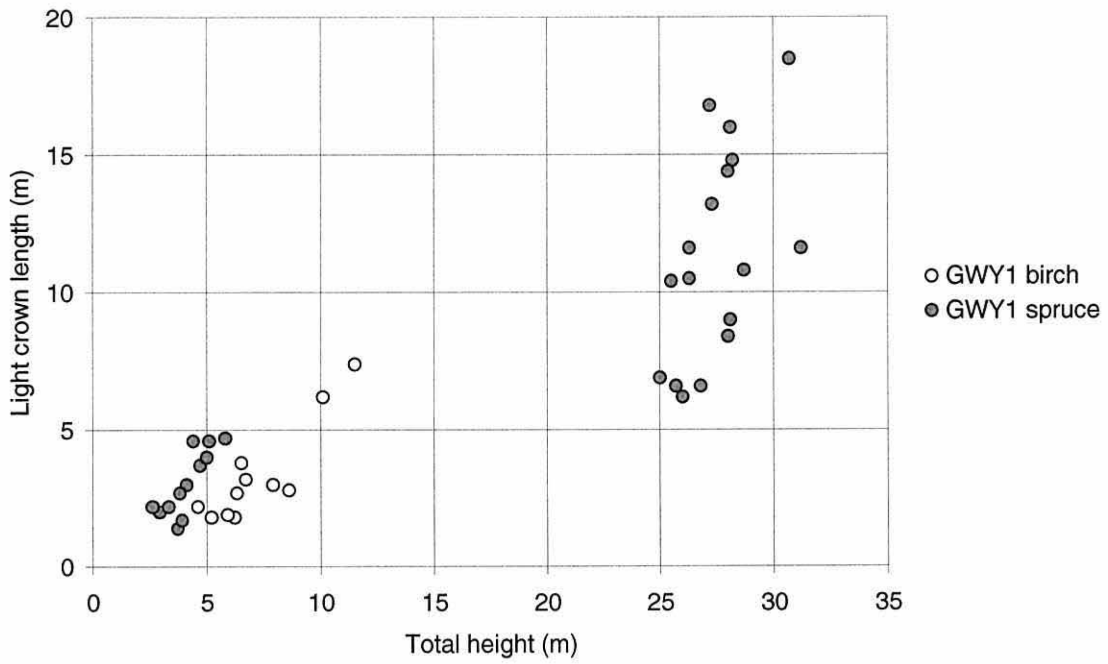
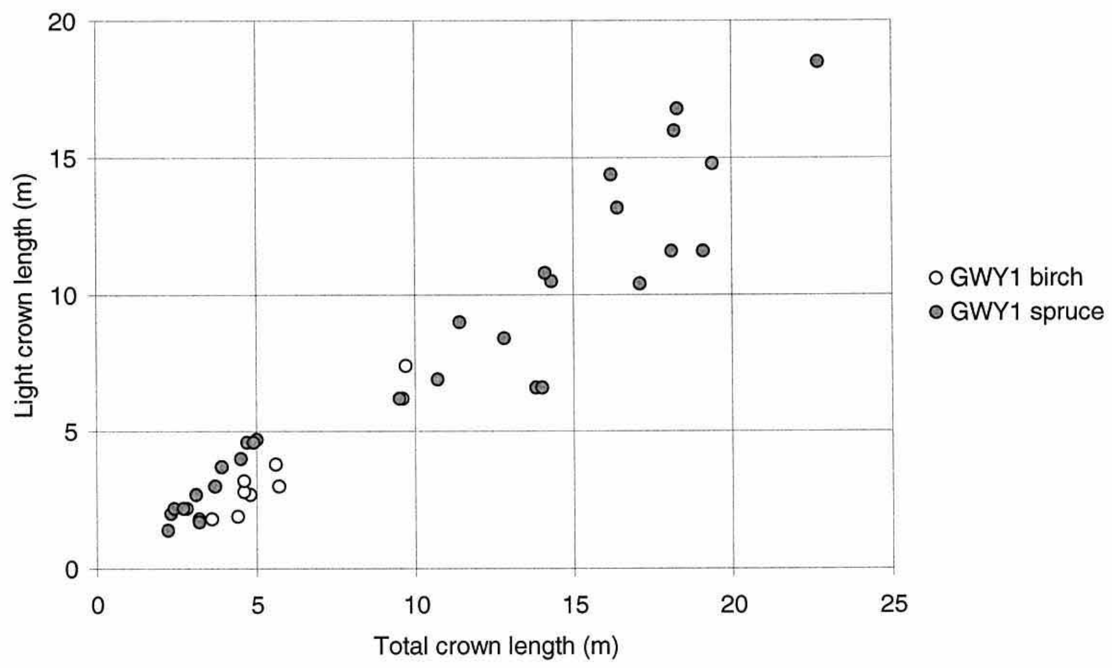


Fig. 4.9 Light crown length plotted against total crown length for GWY1 birch and Sitka spruce crown window sample trees.



Correlations between these dimensions are given in Table 4.9. Maximum crown radius is strongly correlated with *dbh*, particularly for birch. Light crown length is closely correlated with height but is correlated especially strongly with total crown length.

Table 4.9 Stem and crown dimension non-parametric correlations for GWY1 birch and Sitka spruce crown window sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.01 level are marked **; *n* indicates data set size (number of trees).

Crown dimension	Data set	Diameter at breast height, *dbh* (cm)	Total height, *h* (m)	Total crown length, L_{total} (m)
Maximum crown radius, r_{max} (m)	GWY1 birch ($n = 11$)	0.945**	0.755**	0.601
	GWY1 Sitka spruce ($n = 29$)	0.847**	0.866**	0.810**
Light crown length, L_{light} (m)	GWY1 birch ($n = 11$)	0.506	0.838**	0.872**
	GWY1 Sitka spruce ($n = 29$)	0.892**	0.943**	0.968**

4.2.4 *Crown profiles*

Sample profiles and the resulting generalised profiles are shown in Figs. 4.10 and 4.11. In these examples, the light crown makes up 68 % of the total crown length of the birch (Fig. 4.10) and 79 % of the total crown length of the spruce (Fig. 4.11), giving the spruce crown a flatter base. The birch crown maximum radius is 28 % of the crown length, while spruce crown radius is 45 % of total crown length. Some of the variability of birch crown shapes in particular can be observed in the profiles before averaging. Differences in radius at the crown base are obvious between species and also between profiles for the same tree; these differences have an important influence on the performance of shade crown profile models, as models P2 and P3 always give a radius of zero at crown base while P4 can give any value between zero and maximum crown radius.

Fig. 4.10 Sample birch crown profile, showing GWY1 tree 131, L_{total} 5.6 m, r_{max} 1.55 m. The two measured profiles for this tree, a and b, are split into left and right halves. Crown radius (r) is plotted against distance from the point of maximum crown radius (Dr_{max}) of the generalised profile.

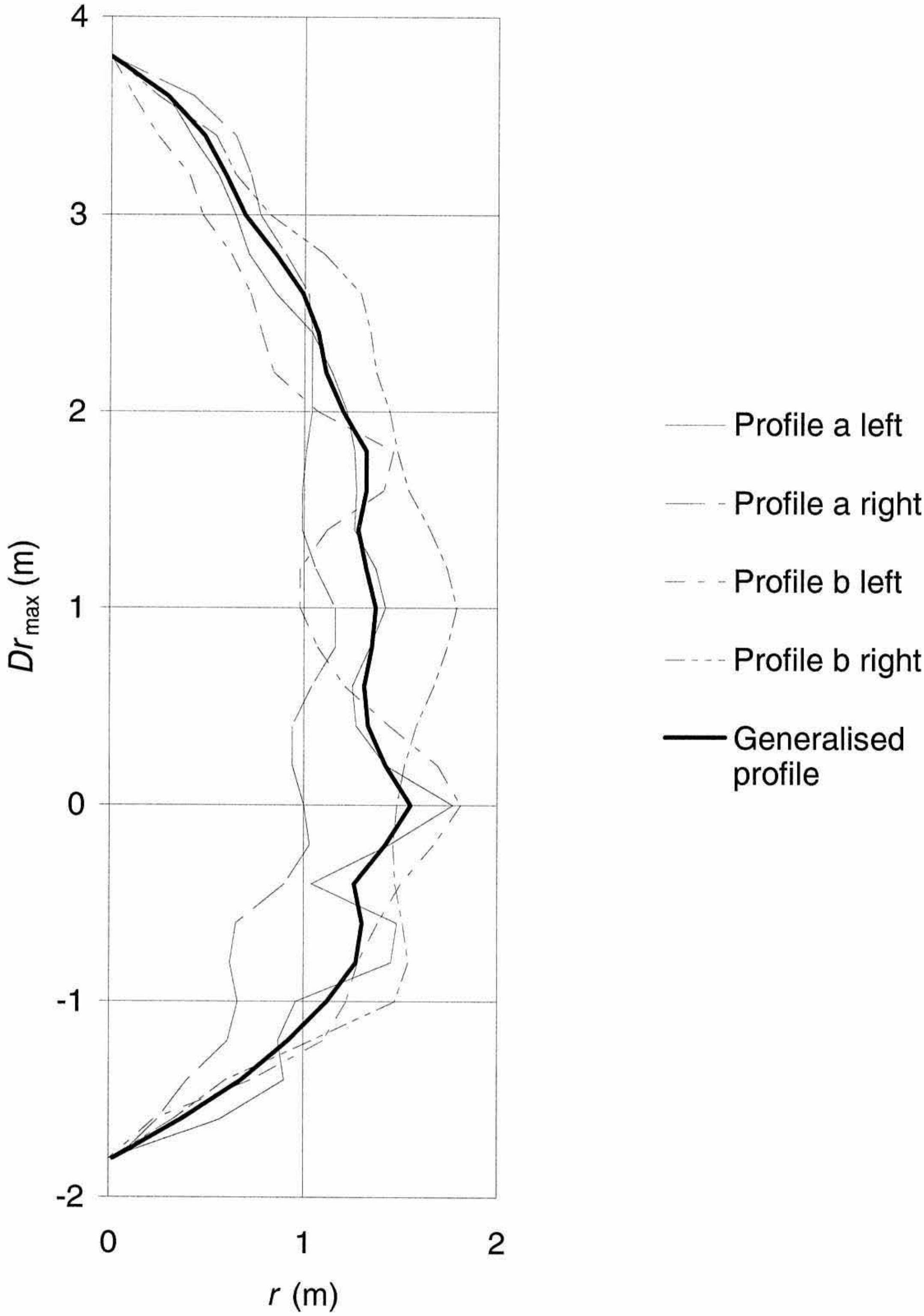
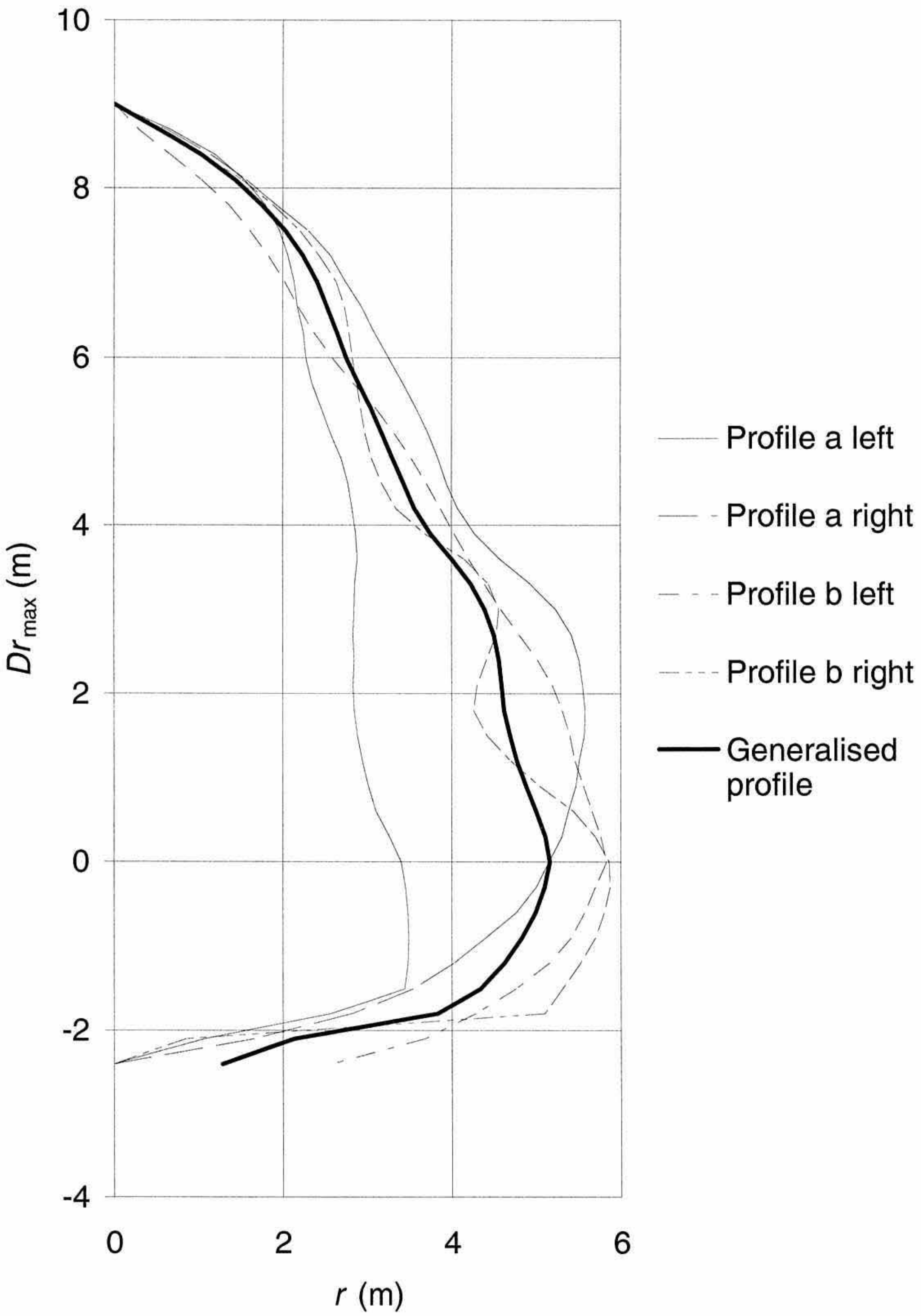


Fig. 4.11 **Sample Sitka spruce crown profile, showing GWY1 tree 511, L_{total} 11.4 m, r_{max} 5.16 m. The two measured profiles for this tree, a and b, are split into left and right halves. Crown radius (r) is plotted against distance from the point of maximum crown radius (Dr_{max}) of the generalised profile.**



4.3 Comparison of crown profile assessment methods

4.3.1 Practical issues

Practical considerations for crown profile assessment fieldwork are described in general in the fieldwork protocol in Appendix I and with specific reference to the sample trees for the comparison of methods in section 3.2.3. The unfortunate timing of birch assessments has already been noted. Spruce crown profile assessments took place in February, when buds were dormant and birch surrounding the sample trees were leafless. An error in setting the zoom of the camera, however, meant that photographs for sample tree 1 were unusable. Repeat photographs were not taken until May, when birch foliage partly obscured the tree and the locations of buds prior to bursting were relatively difficult to identify. None of the sample trees, birch or spruce, could be photographed from an ideal set of camera stations at 45° intervals because of surrounding trees and vegetation. No difficulties were encountered during crown window assessments.

One of the attractive features of photogrammetry is that it allows a great deal of data to be collected with relatively little time spent in the field (although, as noted in section 3.2.2, fieldwork is heavily dependent on weather conditions). Photogrammetric assessments took around 15-20 minutes per tree for the small sample trees in CYB3 and GWY1. Subsequent analysis in PhotoModeler is more time-consuming, however. For the Sitka spruce sample trees, basic analysis times (marking, referencing and troubleshooting ranging rod, leader, branch tip and crown base points) were 260 minutes for tree 1 (58 pts), 205 minutes for tree 2 (43 pts) and 205 minutes for tree 3 (51 pts). Additional analysis times for crown reconstruction (marking and referencing whorl bases and the previous year's leader and branch tips) were 145 minutes for tree 1 (51 pts), 75 minutes for tree 2 (34 pts) and 75 minutes for tree 3 (46 pts). The effect of poorer visibility on analysis times for tree 1 is obvious, as is the remarkable consistency in analysis times for trees 2 and 3 despite differences in the numbers of points modelled. As planned, easily identified ranging rod and upper crown points facilitated early processing of photogrammetry data for all spruce sample trees, allowing the use of tools in PhotoModeler to speed the referencing of subsequent points.

Despite good progress with spruce sample trees, photogrammetric analysis of birch crowns proved to be impracticable; because of the irregularity of the branching structure, branch tips could not be identified on any photographs, let alone cross-referenced across multiple photographs. Even early processing based solely on ranging rod points, which made it easier to locate points on multiple photographs, did not solve the underlying problem of branch tip identification. This is a major failing of photogrammetry, which relies on the marking of discrete, readily identifiable points. It is doubtful whether higher quality images would have overcome this problem, which stems from the structure of the birch trees themselves. Photogrammetric techniques are far better suited, on the whole, to application to simple conifer crowns.

4.3.2 Crown dimension data comparisons

The comparison of methods for birch is limited by the failure of photogrammetric analysis. Table 4.10 shows crown dimension data from direct measurements and crown window assessments. The only paired data are for maximum crown radius, where values from direct measurements are consistently higher. This is contrary to what might be expected, as the crown window measures the maximum visible width of the crown, whereas measured crown radii may fall between directions of maximum crown extent (see section 3.2.5). The mean difference in $r_{\max}$ is significantly different from zero in a paired *t*-test ($p = 0.004$).

Table 4.10 Birch crown dimension data from the comparison of crown profile assessment methods.

Crown dimension	Measurement method	GWY1 birch sample tree		
		1	2	3
Maximum crown radius, $r_{\max}$ (m)	Direct measurement	1.46	1.14	1.58
	Crown window	1.33	1.02	1.43
Total crown length, L_{total} (m)	Direct measurement	3.5	4.1	4.9
Light crown length, L_{light} (m)	Crown window	1.8	2.8	3.0
Shade crown length, L_{shade} (m)	Crown window	1.7	1.3	1.9

Crown dimensions derived for Sitka spruce sample trees by direct measurements, photogrammetry and crown window assessment are shown in Table 4.11. Measurements of total crown length from photogrammetry correspond very well with direct measurements, varying by no more than 0.2 m. The mean difference is not significantly different from zero in a paired *t*-test (p = 0.057). Light and shade crown lengths from photogrammetry and crown window profiles also correspond very well for trees 1 and 2, but crown window data give a slightly longer shade crown for tree 3. An unusually short branch in the ninth whorl reduces the radius of the mean branch tip around the point of crown window r_{max}, whereas an unusually long branch in the tenth whorl increases the radius of the mean branch tip while not affecting the crown window profile; by lowering the point of r_{max} in the photogrammetry model, this increases light crown length and decreases shade crown length relative to crown window values. Despite this, differences in L_{light} and L_{shade} are not significant in paired *t*-tests (p = 0.456 and 0.157 respectively). Differences in crown profile data between these two methods are discussed in section 4.3.3 below. Photogrammetry and crown window estimates of maximum crown radius match closely, the greatest difference being 0.12 m for tree 1, or roughly 10 % (mean difference not significant, p = 0.349). As expected (see section 3.2.5) both photogrammetry and the crown window give higher values for r_{max} than direct measurements (significantly different, p = 0.013 and 0.049 respectively).

Table 4.11 Sitka spruce crown dimension data from the comparison of crown profile assessment methods.

Crown dimension	Measurement method	CYB3 Sitka spruce sample tree		
		1	2	3
Maximum crown radius, r_{max} (m)	Direct measurement	0.94	0.71	0.76
	Photogrammetry	1.13	0.92	0.90
	Crown window	1.25	0.95	0.89
Total crown length, L_{total} (m)	Direct measurement	3.8	2.6	2.8
	Photogrammetry	3.6	2.5	2.7
Light crown length, L_{light} (m)	Photogrammetry	2.8	2.2	2.6
	Crown window	2.9	2.1	2.2
Shade crown length, L_{shade} (m)	Photogrammetry	0.8	0.3	0.1
	Crown window	0.9	0.5	0.6

4.3.3 *Crown profile data comparisons*

Fig. 4.12 shows photogrammetry and crown window crown profile data for the three Sitka spruce sample trees in CYB3. Raw photogrammetry data for each branch tip are shown, as well as the mean branch tip for each whorl (see section 3.2.4). Overall the match between mean branch tips and generalised crown window profiles is good. Both the crown window and photogrammetry can capture some surprisingly subtle changes in crown profile, such the distinctive section between 1.4 and 2.1 m D_{tip} on tree 2 (Fig. 4.12(b)). Where there is a broad horizontal range of branch tips, most obviously in the sixth and seventh whorls of tree 1 (Fig. 4.12(a)), the crown window profile tends to have a greater radius than the mean branch tip, as the method inevitably emphasises the contribution of the longest branches to overall crown width. In whorls with few branches, however, outlying branch tips have greater effects on mean branch tips than on crown window profiles; this effect is most obvious in the ninth and tenth whorls of tree 3 (Fig. 4.12(c)), as described above in section 4.3.2. It may be noted that the generalised crown window profiles extend beyond the lowest mapped branch tip. This reflects the difficulty of identifying foliage perpendicular to the line of sight in the lower reaches of the crown when drawing crown window profiles as well as the fact that there may be a substantial vertical difference between the crown base, at the base of the lowest live branch, and the mean branch tip of the lowest whorl, particularly where branches are relatively young and upright.

Differences in radii derived using the two methods were calculated by subtracting crown window radius from photogrammetry mean branch tip radius, with linear interpolation between crown window measurement intervals where necessary. These differences are small, from -0.11 to 0.01 m (mean -0.04 m) for tree 1, -0.01 to 0.08 m (mean 0.03 m) for tree 2, and -0.07 to 0.10 m (mean 0.04 m) for tree 3, but Wilcoxon signed-ranks matched-pairs tests show that they are significant for trees 1 and 3 (p = 0.021 and 0.041 respectively).

Fig. 4.12 Photogrammetry and crown window profiles, plotting crown radius (r) against distance from crown tip (D_{tip}) for (a) CYB3 Sitka spruce sample tree 1, (b) sample tree 2 and (c) sample tree 3.

(a)

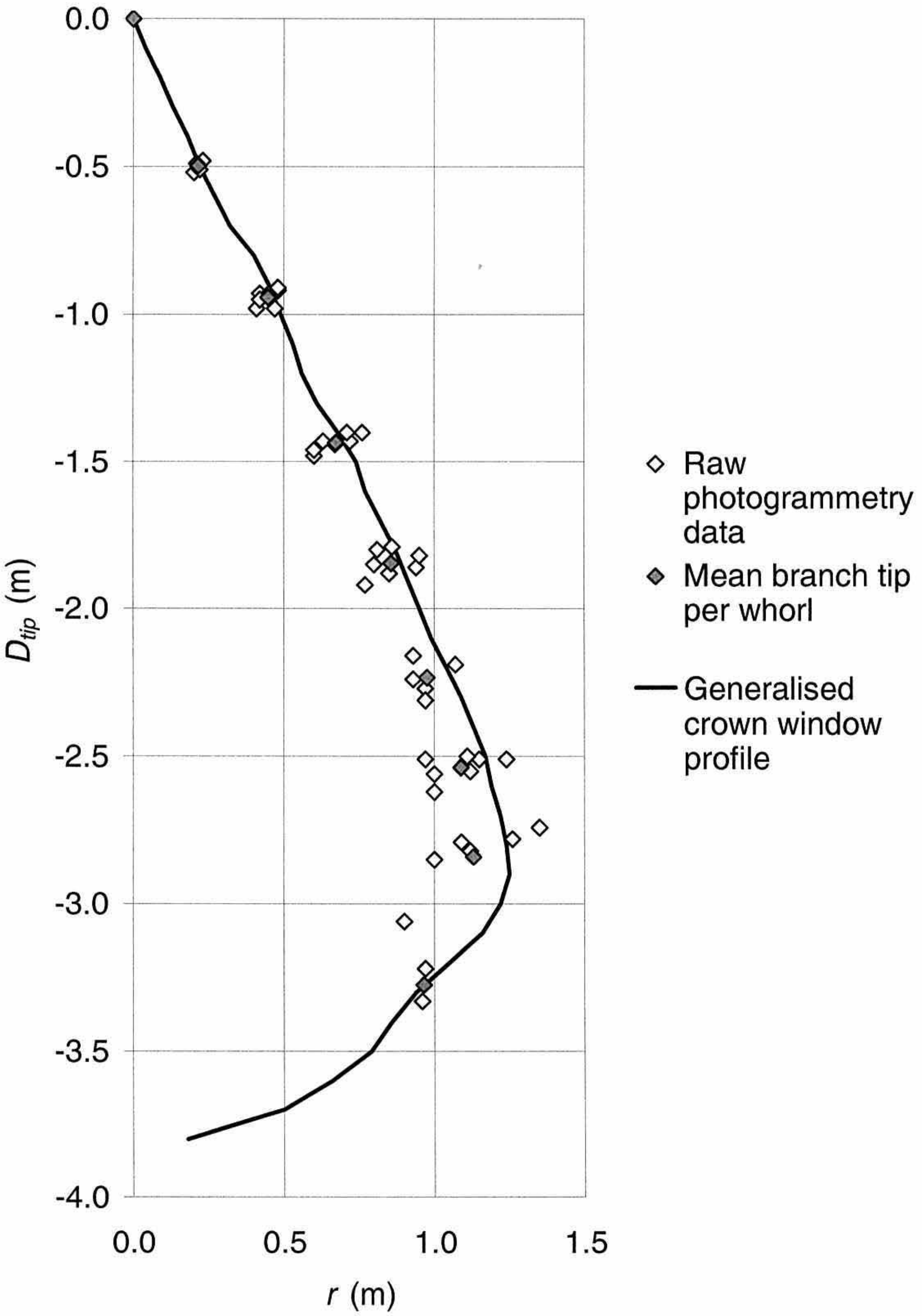
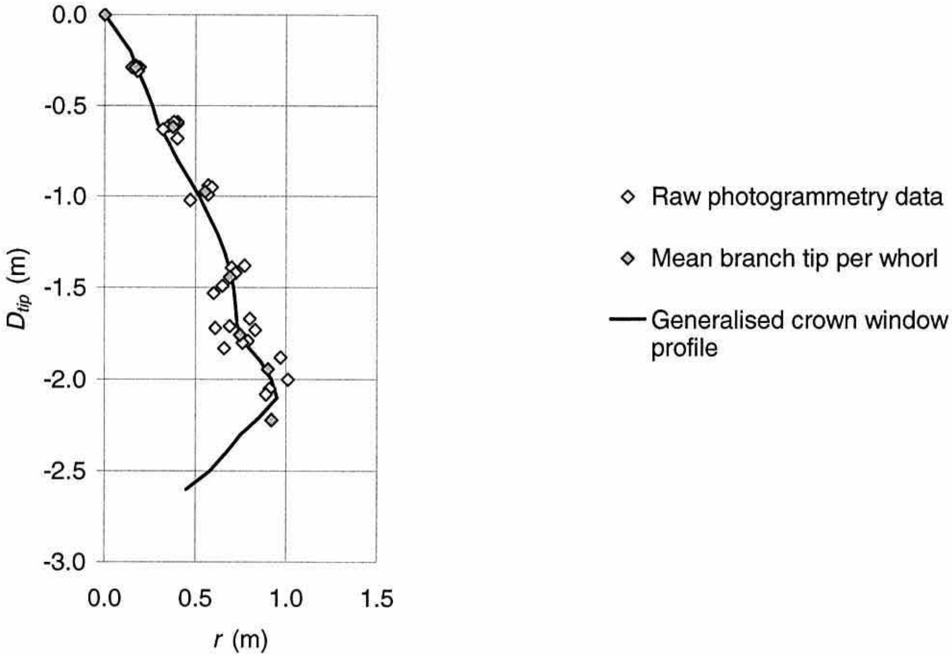
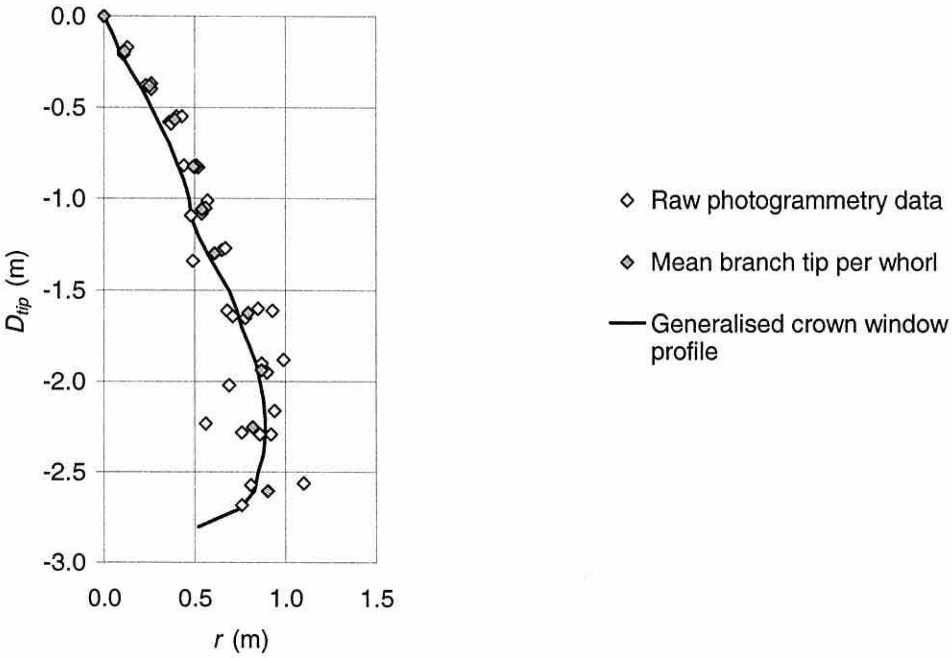


Fig. 4.12 (cont.)

(b)



(c)



Parameter values for light crown profile models P1-3 (see section 3.3.2) parameterised using generalised crown window profile and photogrammetry mean branch tip data are shown in Table 4.12. Light crown length and maximum crown radius values vary slightly between data sources. R^2 values for these parameterisations range from 0.96427 to 0.99965. Paired *t*-tests show no significant differences in mean parameter values between data sources (P1*a* $p = 0.093$, P2*a* $p = 0.173$, P3*a* $p = 0.121$, P3*b* $p = 0.685$).

Table 4.12 Crown profile model parameter values for photogrammetry and crown window data.

Model parameter	Crown profile data source	CYB3 Sitka spruce sample tree		
		1	2	3
P1*a*	Photogrammetry	0.79783	0.70521	0.56704
	Crown window	0.86323	0.86846	0.81064
P2*a*	Photogrammetry	1.29506	1.43321	1.94547
	Crown window	1.19799	1.13531	1.25624
P3*a*	Photogrammetry	1.48300	1.20647	1.77924
	Crown window	1.34534	0.95145	1.23976
P3*b*	Photogrammetry	1.18205	0.82675	0.90552
	Crown window	1.14495	0.83223	0.98505

4.3.4 Crown reconstruction

Crown profile data were also compared for *t* and *t*-1 time periods using photogrammetry data. Crown profiles for both time periods are shown in Fig. 4.13. The profiles diverge in the upper crown where lateral branch extension is greatest, although the overall effect on crown shape is relatively small. It may be noted that the time period *t* leader is retained as the origin of the co-ordinate system, and that the *t*-1 leader is not always directly below it (Fig. 4.13(a) and (b)) because of slight deviations from the vertical in leader extension.

Fig. 4.13 Reconstructed crown profiles, plotting time period *t* and *t*-1 crown radius (*r*) against period *t* distance from crown tip (D_{tip}) for (a) CYB3 Sitka spruce sample tree 1, (b) sample tree 2 and (c) sample tree 3.

(a)

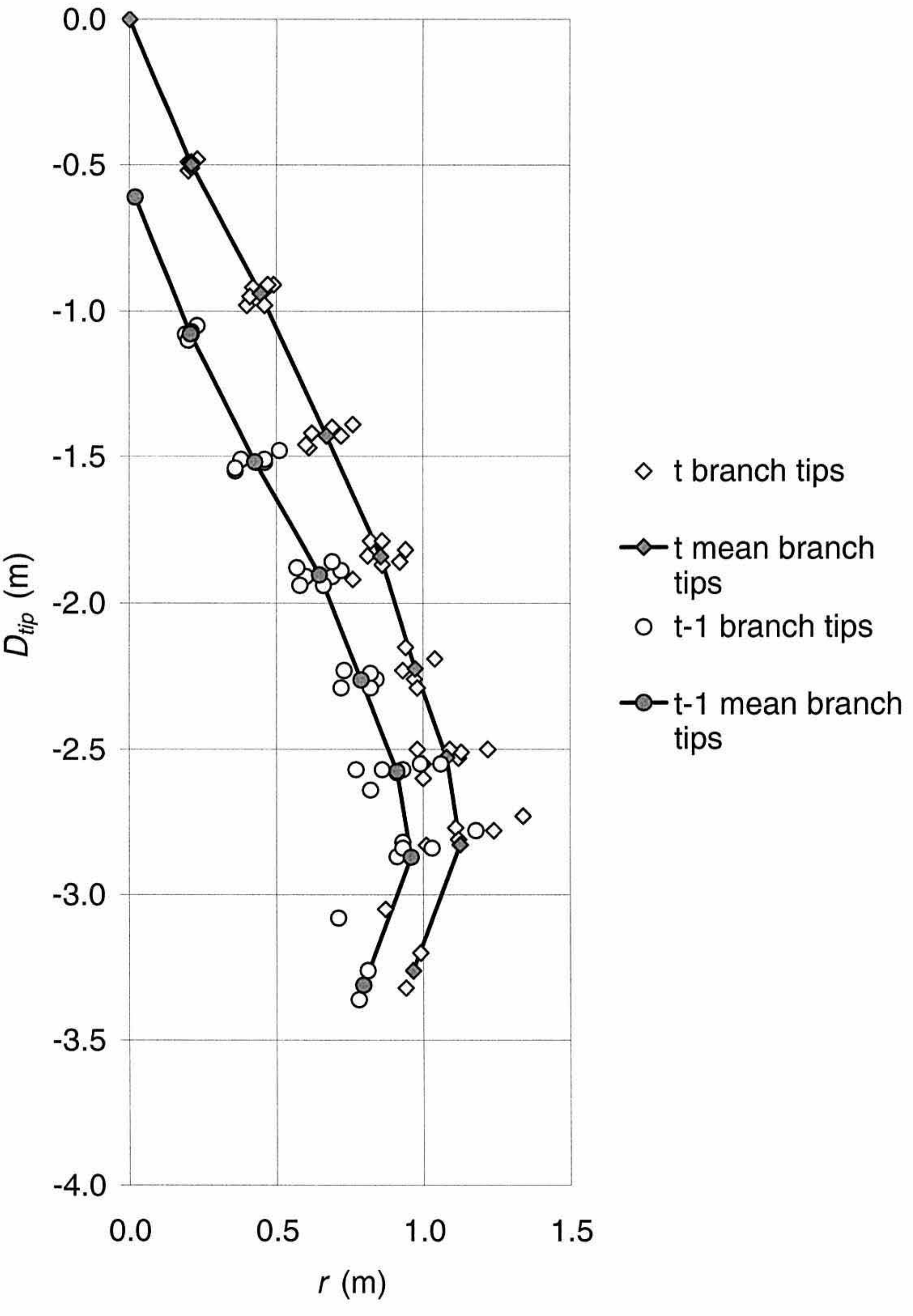
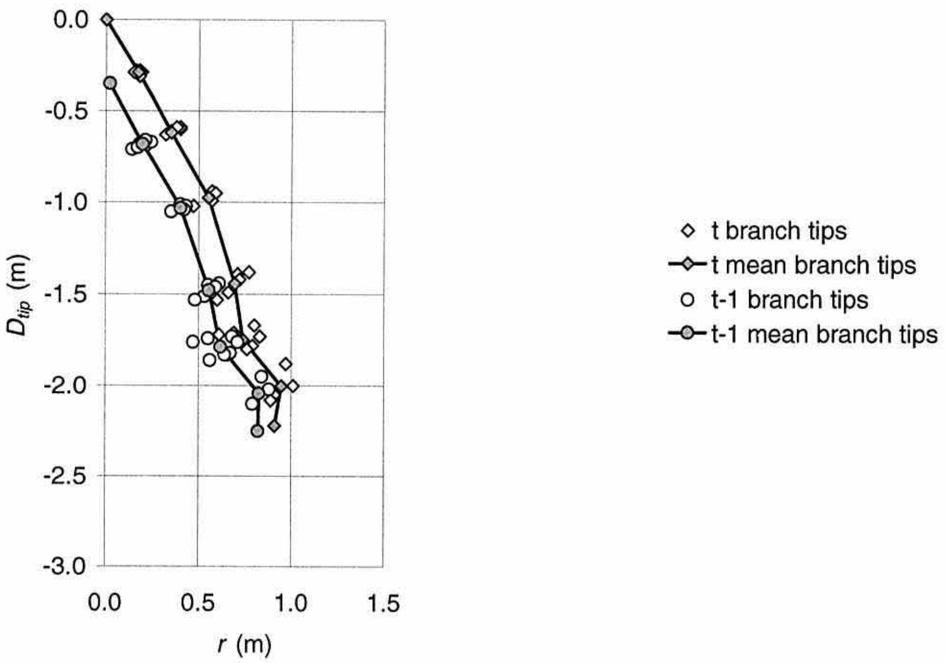
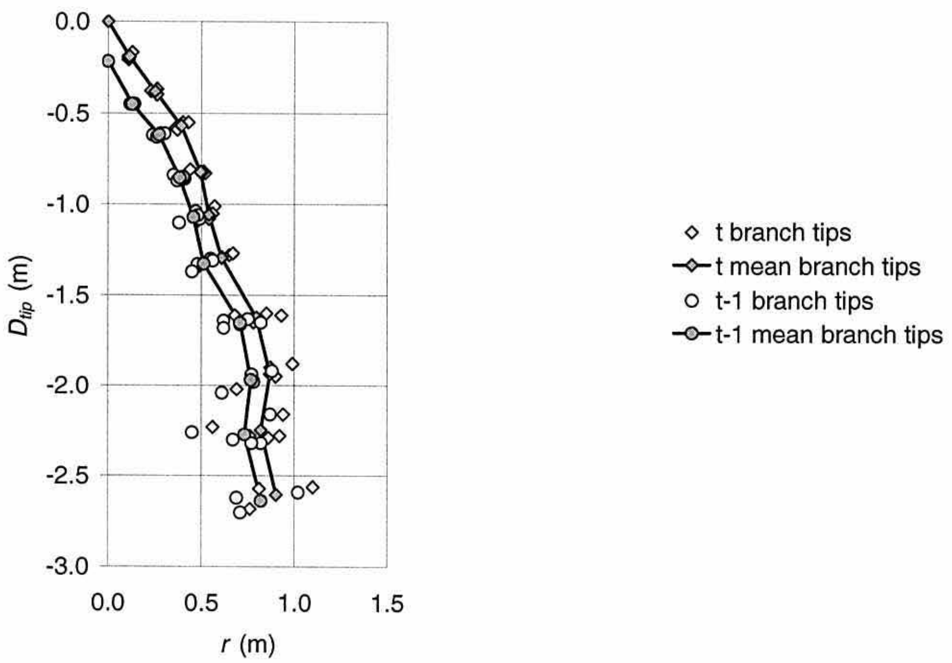


Fig. 4.13 (cont.)

(b)



(c)



Whorl mean absolute branch length increment is plotted against distance from crown tip to whorl base for the three Sitka spruce sample trees in Fig. 4.14. Increment decreases in lower whorls; linear trend lines fitted by least squares have negative slopes and R^2 values of 0.7552 (tree 1), 0.8486 (tree 2) and 0.4787 (tree 3). Trees 1 and 3 show relatively little branch extension in the uppermost whorl, presumably because of preferential growth of the leader. Mean relative branch increment for each whorl (see section 3.2.4) is shown in Fig. 4.15. Relative increment could not be calculated for the uppermost whorl of each tree, which did not exist in the *t*-1 time period. Trends in relative branch extension with distance from the crown tip are obvious; power trend lines of the form $y = a{\cdot}x^{-b}$ give R^2 values of 0.9687 (tree 1), 0.9872 (tree 2) and 0.9104 (tree 3). These strong relationships between whorl position and relative branch increment suggest that there is scope for modelling crown profile dynamically in terms of height growth and branch extension.

Fig. 4.14 Whorl mean absolute branch length increment for CYB3 Sitka spruce sample trees.

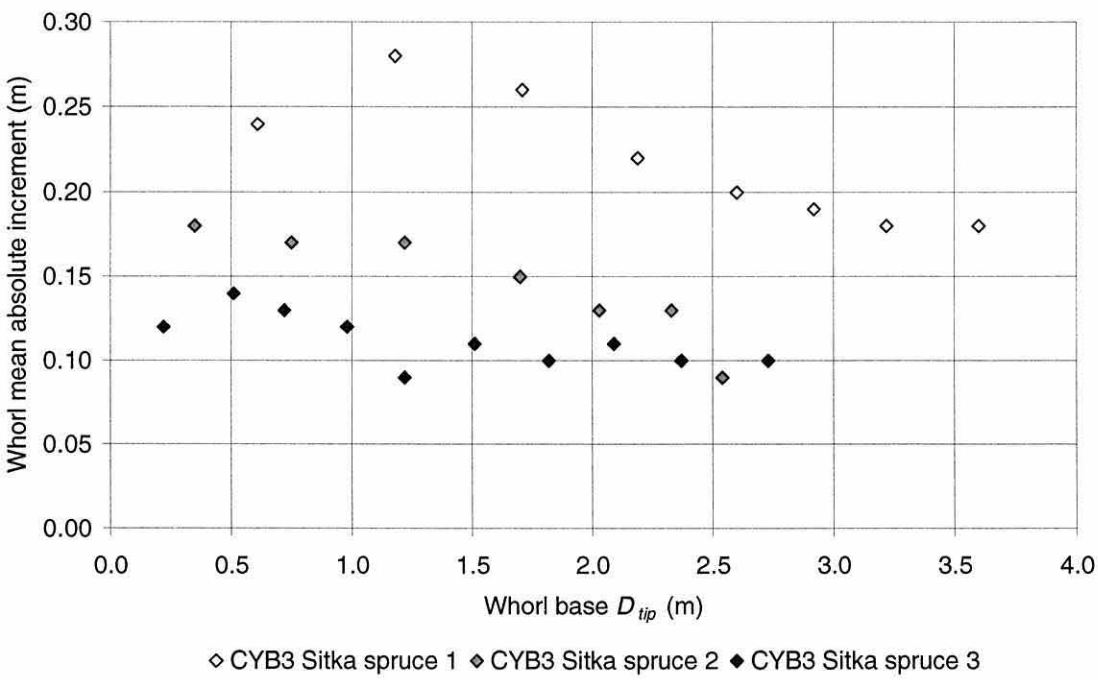


Fig. 4.15 Whorl mean relative branch length increment for CYB3 Sitka spruce sample trees.

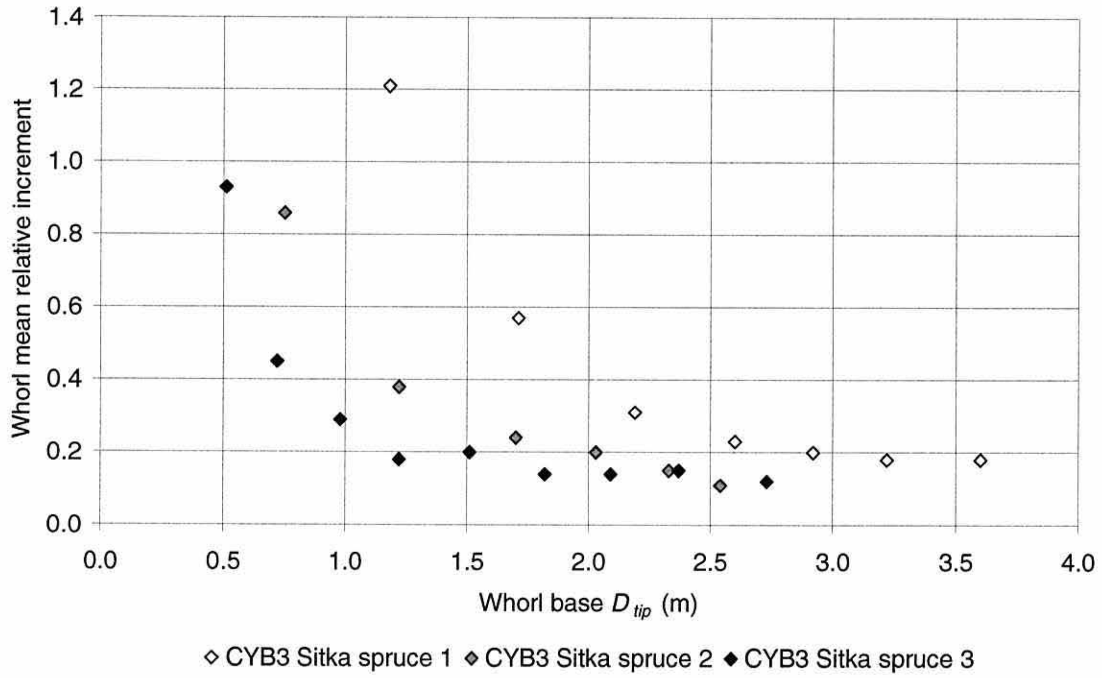


Table 4.13 shows parameter values for crown profile models parameterised for both time periods. Paired *t*-tests show no significant differences in mean parameter values between time periods (P1*a* $p = 0.335$, P2*a* $p = 0.341$, P3*a* $p = 0.404$, P3*b* $p = 0.672$), suggesting minimal change in crown shape, but differences may be seen to be greatest for tree 2, the sample tree with the smallest crown.

Table 4.13 Crown profile model parameter values for *t* and *t*-1 time periods.

Model parameter	Time period	CYB3 Sitka spruce sample tree		
		1	2	3
P1*a*	*t*	0.79783	0.70521	0.56704
	t-1	0.82712	0.91658	0.57237
P2*a*	*t*	1.29506	1.43321	1.94547
	t-1	1.25352	1.00977	1.92432
P3*a*	*t*	1.48300	1.20647	1.77924
	t-1	1.52283	0.60737	1.71546
P3*b*	*t*	1.18205	0.82675	0.90552
	t-1	1.28059	0.62085	0.88249

4.4 Crown dimension modelling

4.4.1 Maximum crown radius model validation results

Results of maximum crown radius model validations for birch are shown in Table 4.14. Although only one validation shows significant bias (CYB1 model R7), there are serious problems with model efficiency for the Coed y Brenin data sets. Almost all efficiency values are negative, indicating that the models have less predictive power than a simple mean. There is no obvious explanation for these failures in terms of differences between parameterisation and validation data sets, although the spectacular failure of model R3 for CYB2 is due to one unusually high *dbh* value in the validation data set. It may simply be that the variability of birch crown dimensions in these mixed plots is too great for the models to account for, given the results of tests of crown shape uniformity and displacement (see section 4.1.2). Parameterisation R^2 values show that models only account for 24-56 % of variation in CYB1 and 4-59 % in CYB2 parameterisation data sets, so these unimpressive validation results are perhaps not surprising. Results are better for GWY1 and the combined data set, though unremarkable. Model R4 has the lowest bias and highest predictive power for GWY1 but is worst in both respects for the combined data set, where R7 performs best.

Results for Sitka spruce are considerably better (Table 4.15), although the Coed y Brenin plots continue to give the worst results. The only models to show significant bias are those based on total height, R2 and R6, for the combined data set. These models give the worst results for all data sets apart from CYB1, suggesting that under most circumstances height alone is a poor predictor of maximum crown radius. Model R1 gives the best accuracy and efficiency for CLG1 spruce, while R7 gives the best accuracy and efficiency for CLG2. For these two data sets, however, most models give very similar efficiency results. R2 gives the best accuracy and efficiency for CYB1, though it only accounts for some 17 % of variation in r_{max}. Results are slightly better for CYB2, the best being for model R7. All results are good for GWY1, particularly for models R3 and R4. For the combined data set, models R1, R3 and R4 all give more or less equally good results. Generally, though, if models R2 and R6 are discounted, there is little basis on which to distinguish model performances.

Table 4.14 Birch maximum crown radius model validation results. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level); *n* indicates data set size (number of trees).

		Model						
Data set	Statistic	R1	R2	R3	R4	R5	R6	R7
CYB1 ($n = 12$)	% Bias	10.18	5.82	6.94	7.19	9.82	6.07	26.01*
	% Acc.	24.86	32.30	22.22	23.12	25.23	32.86	43.19
	Eff.	-0.26	-1.11	0.00	-0.09	-0.30	-1.18	-2.88
CYB2 ($n = 12$)	% Bias	18.67	-22.27	2357.09	99.07	16.76	-20.45	15.38
	% Acc.	36.59	42.43	8098.43	260.29	31.47	40.15	42.71
	Eff.	-0.32	-0.78	-63671.85	-65.14	0.02	-0.59	-0.78
GWY1 ($n = 12$)	% Bias	3.96	-6.88	2.98	2.17	3.62	-7.18	5.40
	% Acc.	13.81	15.33	12.14	10.74	13.10	15.57	14.32
	Eff.	0.42	0.28	0.55	0.65	0.48	0.25	0.37
All plots ($n = 37$)	% Bias	4.56	-2.98	1.16	13.54	4.26	-3.11	2.72
	% Acc.	39.57	39.60	29.97	79.48	39.39	39.23	24.08
	Eff.	0.01	0.01	0.43	-2.99	0.02	0.03	0.63

Table 4.15 Sitka spruce maximum crown radius model validation results. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level); *n* indicates data set size (number of trees).

		Model						
Data set	Statistic	R1	R2	R3	R4	R5	R6	R7
CLG1 (n = 25)	% Bias % Acc. Eff.	0.20 13.32 0.58	2.22 17.26 0.29	0.15 13.59 0.56	0.24 13.56 0.56	0.23 13.33 0.57	2.27 17.21 0.29	-1.41 13.57 0.56
CLG2 (n = 12)	% Bias % Acc. Eff.	1.33 14.33 0.56	5.56 16.35 0.42	0.04 13.89 0.58	0.01 13.93 0.58	1.37 15.40 0.49	5.87 17.01 0.37	-1.83 13.83 0.59
CYB1 (n = 12)	% Bias % Acc. Eff.	6.96 22.42 0.15	9.24 22.05 0.17	6.46 22.15 0.17	6.46 22.16 0.17	7.63 22.87 0.11	9.23 22.26 0.16	6.55 23.28 0.08
CYB2 (n = 12)	% Bias % Acc. Eff.	5.96 22.68 0.24	14.46 31.96 -0.52	6.24 23.24 0.21	6.18 22.84 0.23	6.00 22.44 0.26	14.58 31.76 -0.50	5.75 21.29 0.33
GWY1 (n = 14)	% Bias % Acc. Eff.	-0.33 15.64 0.77	2.05 17.70 0.70	0.44 15.24 0.78	0.46 15.11 0.78	-1.12 16.38 0.75	1.89 17.58 0.71	-1.37 16.62 0.74
All plots (n = 77)	% Bias % Acc. Eff.	-1.15 16.55 0.77	-5.88* 23.86 0.53	-1.20 16.56 0.77	-1.31 16.62 0.77	-1.52 17.27 0.75	-6.40* 24.60 0.50	-0.55 17.15 0.76

4.4.2 *Total crown length model validation results*

Total crown length modelling results for birch (Table 4.16) are marginally better than radius modelling results. Efficiency values for CYB1 are positive, if unimpressive; model L3 gives the best results, accounting for 42 % of variation in crown length (L4 gives the same results because the regression coefficient *c* was parameterised to zero). Only model L3 gives acceptable results for CYB2, all other models giving significant biases and negative efficiencies, but gives an efficiency of only 0.29. Results are far superior for GWY1, where all models account for 80 % or more of variation without any significant biases; model L4 performs best overall. Results for the combined data set are mixed, with L3 giving the best accuracy and efficiency values (as with CYB1, L3 and L4 give identical results).

Results are good for spruce (Table 4.16). Model L3 gives the best results for CLG1 and CLG2, accounting for 64 and 65 % of variation in L_{total} respectively. Only L3 gives unbiased results CYB1, with an acceptable efficiency of 0.53, and also gives the best results for CYB2. All models perform extremely well with GWY1 data, accounting for 89-90 % of variation in all cases; L2 has a slight edge in terms of accuracy. Model L3 again gives the best results for the combined data set, giving the best accuracy and efficiency figures; although the bias is higher than for models L1-2 it is not significant.

4.4.3 *Light crown length model validation results*

Light crown modelling results based on crown window profiles for GWY1 birch and spruce are shown in Table 4.17. Model LL4 gives the best results (highest efficiency and lowest accuracy) for birch and LL2 is best for spruce, but in both cases very little improvement is made over the simplest model, LL1, which accounts for 89 % of variation in light crown length for birch and 91 % for spruce. The parameterisations for this model suggest that light crown length is generally 68 % of total crown length for birch and 76 % of total crown length for spruce.

Table 4.16 Birch and Sitka spruce total crown length model validation results. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level) or ** (0.01 level); *n* indicates data set size (number of trees).

		Model			
Data set	Statistic	L1	L2	L3	L4
CYB1 birch (n = 12)	% Bias % Acc. Eff.	-4.90 50.95 0.34	-5.45 50.31 0.36	-8.46 47.51 0.42	-8.46 47.51 0.42
CYB2 birch (n = 12)	% Bias % Acc. Eff.	-23.46* 38.95 -1.25	-17.53* 28.21 -0.18	0.02 22.19 0.29	-24.89* 41.31 -1.53
GWY1 birch (n = 12)	% Bias % Acc. Eff.	2.28 18.92 0.81	4.41 19.59 0.80	7.75 19.15 0.81	3.23 16.65 0.86
All plots birch (n = 37)	% Bias % Acc. Eff.	3.33 40.61 0.03	4.19 34.39 0.30	7.03 30.06 0.47	7.03 30.06 0.47
CLG1 Sitka spruce (n = 25)	% Bias % Acc. Eff.	-1.69 20.47 0.37	-2.17 19.29 0.44	-2.92 15.37 0.64	-2.81 15.45 0.64
CLG2 Sitka spruce (n = 12)	% Bias % Acc. Eff.	10.03 22.99 0.50	9.16 22.28 0.53	5.65 19.35 0.65	7.21 20.52 0.60
CYB1 Sitka spruce (n = 12)	% Bias % Acc. Eff.	13.84** 19.79 0.52	12.77* 19.55 0.54	10.28 19.73 0.53	10.53* 19.54 0.54
CYB2 Sitka spruce (n = 12)	% Bias % Acc. Eff.	5.89 17.53 0.38	4.88 16.46 0.45	2.54 14.98 0.55	2.54 14.98 0.55
GWY1 Sitka spruce (n = 14)	% Bias % Acc. Eff.	-0.51 21.36 0.90	-0.56 20.96 0.90	-6.96 22.13 0.89	-6.87 22.10 0.89
All plots Sitka spruce (n = 77)	% Bias % Acc. Eff.	-0.81 23.08 0.62	-0.15 21.70 0.67	2.52 21.45 0.67	2.52 21.45 0.67

Table 4.17 Birch and Sitka spruce light crown length model validation results. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. *n* indicates data set size (number of trees).

Data set	Statistic	Model LL1	LL2	LL3	LL4
GWY1 birch (n = 5)	% Bias % Acc. Eff.	11.16 17.47 0.89	19.65 26.52 0.74	15.85 20.62 0.84	2.01 14.83 0.93
GWY1 Sitka spruce (n = 14)	% Bias % Acc. Eff.	5.69 21.00 0.91	9.69 20.18 0.91	9.88 20.21 0.91	4.20 22.97 0.89

4.4.4 *Relationships with spatial variables*

The results of non-parametric correlation analyses for birch maximum crown radius, stem dimensions and spatial variables are shown in Table 4.18. The directions of relationships with r_{max} are consistent across all data sets for the variables *dbh* (positive), height (positive), basal area of larger trees (negative) and the Hegyi index for 0.01 ha, 0.02 ha (GWY1 only) and height angle competitor selection (negative), but only the correlations with *dbh* and *BAL* are consistently statistically significant. These results suggest that larger trees tend to have wider crowns, but that greater competition, indicated by higher values of *BAL* and the Hegyi index, has a negative effect on crown width. Similar relationships may be observed for Sitka spruce (Table 4.19). Correlations are consistently positive for *dbh*, *h*, *HDist*, *Udbh* and *Uh*, variables representing tree size, distance from competitors, and dominance. Relationships with *dbh* and *h* are consistently significant. Correlations are consistently negative with $N_{0.01}$, $N_{0.02}$, $BA_{0.01}$ (with the sole exception of CYB2), $BA_{0.02}$, *BAL*, $Hg_{0.01}$, $Hg_{0.02}$, N_{HA}, BAL_{HA} and Hg_{HA}, all representing the competitive influence of surrounding trees. These relationships are consistently significant for *BAL*, $Hg_{0.01}$, $Hg_{0.02}$ and Hg_{HA}. For both species, relationships with *dbh* tend to be stronger than those with other variables (as shown by magnitudes of the correlation coefficient), suggesting that *dbh* would dominate any models, particularly since it is strongly correlated with most other variables. The stronger and more significant correlations for Sitka spruce suggest that r_{max} models incorporating spatial variables for this species may have greater predictive power than those for birch.

Table 4.18 Birch maximum crown radius and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set			
	CYB1 ($n = 25$)	CYB2 ($n = 25$)	GWY1 ($n = 25$)	All plots ($n = 75$)
dbh (cm)	0.411*	0.564**	0.875**	0.623**
h (m)	0.289	0.246	0.640**	-0.271*
HDist (m)	0.187	-0.106	-0.078	0.501**
W	0.136	-0.003	0.343	0.055
M	0.140	-0.061	-0.332	0.010
Udbh	0.164	0.214	0.645**	0.105
Uh	-0.029	0.044	0.525**	0.044
$N_{0.01}$ (stems ha^{-1})	-0.181	-0.351	0.215	-0.702**
$N_{0.02}$ (stems ha^{-1})	-	-	0.180	0.180
$BA_{0.01}$ (m^2 ha^{-1})	0.300	-0.359	-0.082	-0.109
$BA_{0.02}$ (m^2 ha^{-1})	-	-	-0.010	-0.010
BAL (m^2 ha^{-1})	-0.405*	-0.666**	-0.853**	-0.758**
$Hg_{0.01}$	-0.497*	-0.791**	-0.356	-0.818**
$Hg_{0.02}$	-	-	-0.489*	-0.489*
N_{HA} (stems)	0.042	-0.420*	-0.044	-0.608**
BA_{HA} (m^2)	0.126	-0.332	-0.354	0.305**
BAL_{HA} (m^2)	0.123	-0.437*	-0.361	0.268*
Hg_{HA}	-0.378	-0.684**	-0.472*	-0.650**

Table 4.19 Sitka spruce maximum crown radius and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient; correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that there was no species mingling in plot CLG1 and that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set					
	CLG1 (n = 50)	CLG2 (n = 25)	CYB1 (n = 25)	CYB2 (n = 25)	GWY1 (n = 29)	All plots (n = 154)
dbh (cm)	0.762**	0.768**	0.604**	0.889**	0.949**	0.862**
h (m)	0.517**	0.497**	0.579**	0.686**	0.809**	0.778**
HDist (m)	0.085	0.649**	0.572**	0.237	0.537**	0.687**
W	0.173	0.251	0.004	0.313	-0.212	-0.034
M	-	-0.247	0.083	-0.082	-0.357	-0.345**
Udbh	0.688**	0.441*	0.136	0.608**	0.876**	0.196*
Uh	0.413**	0.474*	0.145	0.635**	0.928**	0.215**
$N_{0.01}$ (stems ha^{-1})	-0.182	-0.719**	-0.354	-0.303	-0.576**	-0.748**
$N_{0.02}$ (stems ha^{-1})	-0.192	-0.572**	-	-	-0.554**	-0.358**
$BA_{0.01}$ (m^2 ha^{-1})	-0.132	-0.513**	-0.055	0.147	-0.485**	-0.603**
$BA_{0.02}$ (m^2 ha^{-1})	-0.072	-0.447*	-	-	-0.280	-0.139
BAL (m^2 ha^{-1})	-0.763**	-0.658**	-0.594**	-0.874**	-0.928**	-0.439**
$Hg_{0.01}$	-0.337*	-0.746**	-0.693**	-0.885**	-0.880**	-0.846**
$Hg_{0.02}$	-0.584**	-0.771**	-	-	-0.853**	-0.756**
N_{HA} (stems)	-0.253	-0.592**	-0.157	-0.246	-0.183	-0.612**
BA_{HA} (m^2)	-0.151	-0.190	0.048	-0.086	0.151	0.427**
BAL_{HA} (m^2)	-0.626**	-0.340	-0.119	-0.715**	-0.545**	-0.093
Hg_{HA}	-0.562**	-0.795**	-0.480*	-0.792**	-0.681**	-0.830**

Correlations for total crown length (Tables 4.20 and 4.21) show broadly similar relationships with stem dimensions and spatial variables. For birch, *dbh*, *h*, *Udbh* and *Uh* show consistent positive correlations with L_{total}, with *dbh* and *h* relationships consistently significant. *BAL*, $Hg_{0.01}$ and Hg_{HA} are consistently negatively correlated with L_{total}, and all *BAL* correlations are significant. Spruce crown length is consistently positively correlated with *dbh*, *h*, *HDist*, *Udbh* and *Uh*, with *dbh*, *h* and *Uh* showing significant correlations for all data sets. Consistent negative correlations may be observed with *M* (with the exception of CYB1), $N_{0.01}$, $N_{0.02}$, *BAL*, $Hg_{0.01}$, $Hg_{0.02}$, N_{HA} (except CYB1), BAL_{HA} and Hg_{HA}. Of these variables, relationships are consistently significant for *BAL*, $Hg_{0.01}$, $Hg_{0.02}$ and Hg_{HA}. Although the overall relationships with tree size and competition are very similar to those for maximum crown radius, of particular note are the greater consistency, strength and significance of relationships with *Uh*. In part these observations reflect the influence of absolute tree size on crown length, but they also correspond with the capacity of emergent trees to retain live branches along a greater proportion of the stem. As with r_{max}, correlations with L_{total} are generally stronger and more significant for spruce than for birch.

Modelling of total crown length rather than height to crown base was pursued primarily because data limitations ruled out *hcb* increment modelling and because early model parameterisations gave higher R^2 values for L_{total} than for *hcb*. Tables 4.22 and 4.23 show that correlations with *hcb* are far less consistent than those with L_{total}. For birch (Table 4.22), only the variables $Hg_{0.01}$, N_{HA} and Hg_{HA} show both consistent direction of correlation and at least one significant correlation. For Sitka spruce (Table 4.23), only BA_{HA} meets these criteria. In all cases these are positive correlations, demonstrating that crown base recession increases in the presence of greater pressure from competitors. Relationships with tree size and dominance, however, may be confounded by the fact that, although height to crown base will generally increase with tree size under closed forest conditions, larger trees tend to be the most dominant, with greater dominance potentially slowing the rate of crown base recession.

Table 4.20 Birch total crown length and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set			
	CYB1 (n = 25)	CYB2 (n = 25)	GWY1 (n = 25)	All plots (n = 75)
dbh (cm)	0.764**	0.468*	0.667**	0.639**
h (m)	0.807**	0.663**	0.925**	0.563**
HDist (m)	-0.108	-0.080	0.081	0.083
W	0.133	0.250	0.196	0.142
M	-0.343	0.127	-0.260	-0.124
Udbh	0.325	0.420*	0.526**	0.364**
Uh	0.421*	0.193	0.554**	0.354**
$N_{0.01}$ (stems ha^{-1})	0.062	-0.016	0.171	-0.094
$N_{0.02}$ (stems ha^{-1})	-	-	0.181	0.181
$BA_{0.01}$ (m² ha^{-1})	0.548**	-0.072	0.027	0.162
$BA_{0.02}$ (m² ha^{-1})	-	-	0.243	0.243
BAL (m² ha^{-1})	-0.779**	-0.453*	-0.591**	-0.583**
$Hg_{0.01}$	-0.520**	-0.380	-0.209	-0.327**
$Hg_{0.02}$	-	-	-0.263	-0.263
N_{HA} (stems)	0.281	-0.073	0.133	0.017
BA_{HA} (m²)	0.346	0.149	-0.093	0.186
BAL_{HA} (m²)	0.296	0.042	-0.098	0.130
Hg_{HA}	-0.199	-0.208	-0.325	-0.247*

Table 4.21 Sitka spruce total crown length and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that there was no species mingling in plot CLG1 and that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set					
	CLG1 (n = 50)	CLG2 (n = 25)	CYB1 (n = 25)	CYB2 (n = 25)	GWY1 (n = 29)	All plots (n = 154)
dbh (cm)	0.728**	0.596**	0.783**	0.790**	0.908**	0.865**
h (m)	0.827**	0.820**	0.883**	0.808**	0.965**	0.876**
HDist (m)	0.050	0.435*	0.469*	0.169	0.478**	0.550**
W	0.358*	0.197	-0.164	0.342	-0.157	-0.005
M	-	-0.078	0.252	-0.256	-0.389*	-0.409**
Udbh	0.690**	0.479*	0.387	0.465*	0.799**	0.329**
Uh	0.673**	0.567**	0.449*	0.495*	0.840**	0.419**
$N_{0.01}$ (stems ha^{-1})	-0.153	-0.509**	-0.033	-0.501*	-0.494**	-0.577**
$N_{0.02}$ (stems ha^{-1})	-0.083	-0.247	-	-	-0.523**	-0.318**
$BA_{0.01}$ (m² ha^{-1})	-0.099	-0.474*	0.092	0.204	-0.356	-0.394**
$BA_{0.02}$ (m² ha^{-1})	0.034	-0.205	-	-	-0.341	-0.111
BAL (m² ha^{-1})	-0.743**	-0.642**	-0.793**	-0.822**	-0.891**	-0.608**
$Hg_{0.01}$	-0.310*	-0.628**	-0.687**	-0.805**	-0.805**	-0.742**
$Hg_{0.02}$	-0.464**	-0.554**	-	-	-0.805**	-0.669**
N_{HA} (stems)	-0.322*	-0.492*	0.036	-0.418*	-0.051	-0.382**
BA_{HA} (m²)	-0.199	-0.233	-0.017	-0.018	0.241	0.334**
BAL_{HA} (m²)	-0.607**	-0.325	-0.308	-0.516**	-0.446*	-0.165*
Hg_{HA}	-0.576**	-0.661**	-0.495*	-0.705**	-0.625**	-0.747**

Table 4.22 Birch height to crown base and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set			
	CYB1 (n = 25)	CYB2 (n = 25)	GWY1 (n = 25)	All plots (n = 75)
dbh (cm)	-0.261	0.226	-0.014	-0.234*
h (m)	-0.073	0.377	0.035	0.557**
HDist (m)	0.108	-0.332	-0.122	-0.591**
W	0.074	-0.317	0.077	-0.051
M	0.226	-0.127	-0.242	-0.066
Udbh	0.002	0.246	0.086	0.165
Uh	0.042	0.537**	-0.038	0.161
$N_{0.01}$ (stems ha^{-1})	-0.367	0.348	-0.156	0.676**
$N_{0.02}$ (stems ha^{-1})	-	-	0.351	0.351
$BA_{0.01}$ (m² ha^{-1})	-0.020	0.180	0.083	0.173
$BA_{0.02}$ (m² ha^{-1})	-	-	0.116	0.116
BAL (m² ha^{-1})	0.263	-0.114	-0.192	0.465**
$Hg_{0.01}$	0.199	0.231	0.038	0.634**
$Hg_{0.02}$	-	-	0.116	0.116
N_{HA} (stems)	0.177	0.469*	0.096	0.696**
BA_{HA} (m²)	0.231	0.093	-0.027	-0.325**
BAL_{HA} (m²)	0.234	0.070	-0.034	-0.354**
Hg_{HA}	0.287	0.384	0.007	0.512**

Table 4.23 Sitka spruce height to crown base and spatial variable non-parametric correlations for crown survey sample trees, showing values of the Spearman correlation coefficient. Correlations significant at the 0.05 level are marked *, and those significant at the 0.01 level are marked **; *n* indicates data set size (number of trees). For descriptions of spatial variables, see Table 3.7. Note that there was no species mingling in plot CLG1 and that variables $N_{0.02}$, $BA_{0.02}$ and $Hg_{0.02}$ were not calculated for CYB1 and CYB2 data sets.

Stem dimension/ spatial variable	Data set					
	CLG1 (n = 50)	CLG2 (n = 25)	CYB1 (n = 25)	CYB2 (n = 25)	GWY1 (n = 29)	All plots (n = 154)
dbh (cm)	-0.164	0.052	0.372	-0.041	0.635**	0.671**
h (m)	-0.113	-0.013	0.510**	0.067	0.597**	0.726**
HDist (m)	-0.061	-0.009	0.049	0.062	0.254	0.613**
W	-0.026	-0.196	-0.164	-0.427*	0.020	-0.194*
M	-	-0.666**	-0.033	0.214	-0.679**	-0.721**
Udbh	-0.201	-0.180	0.361	0.057	0.482**	-0.134
Uh	-0.037	-0.001	0.366	-0.096	0.659**	-0.001
$N_{0.01}$ (stems ha^{-1})	0.230	0.053	0.050	0.609**	-0.662**	-0.603**
$N_{0.02}$ (stems ha^{-1})	0.286*	-0.154	-	-	-0.616**	-0.221*
$BA_{0.01}$ (m² ha^{-1})	0.139	0.475*	0.357	0.376	-0.418*	-0.361**
$BA_{0.02}$ (m² ha^{-1})	0.071	0.176	-	-	-0.120	-0.037
BAL (m² ha^{-1})	0.182	0.011	-0.330	0.152	-0.600**	-0.019
$Hg_{0.01}$	0.204	0.241	-0.142	0.378	-0.757**	-0.643**
$Hg_{0.02}$	0.233	0.109	-	-	-0.735**	-0.138
N_{HA} (stems)	0.453**	0.289	0.163	0.640**	0.103	-0.149
BA_{HA} (m²)	0.295*	0.547**	0.347	0.526**	0.343	0.626**
BAL_{HA} (m²)	0.322*	0.457*	0.089	0.391	-0.095	0.335**
Hg_{HA}	0.362**	0.187	0.010	0.384	-0.483**	-0.520**

4.4.5 Alternative model forms

The majority of stepwise linear regressions to predict maximum crown radius from stem dimensions and spatial variables returned regressions equivalent to model R1, a simple linear relationship with *dbh*, with no significant improvements in model performance arising from the incorporation of other variables. Novel models were produced for only four of the ten birch and spruce data sets, and are shown along with validation results in Table 4.24. These may be compared with the validation results for models R1-7 given in Tables 4.14 and 4.15. The results for the novel model for the CYB1 birch data set are just as poor as those for the existing models in terms of accuracy and efficiency, despite the inclusion of three independent variables. The model for the CYB2 birch data set incorporating basal area of larger trees, however, gives a far better efficiency (albeit with a significant bias) than any of the models based on stem dimensions. In this plot, the suppression of the birch by the more dominant conifers is evidently the single most important factor limiting the horizontal extent of their crowns, hence the negative relationship with *BAL*. The novel model for the combined birch data set performs less well than model R7 (with an efficiency of 0.63), but the variables selected for inclusion are of some interest. Competitive effects are again seen to be important, in this case in the form of a negative relationship with the Hegyi index. In this instance, the selection of competitors in a fixed circular plot of 0.01 ha is favoured over height angle competitor selection. The inclusion of species mingling, *M*, again associated with a negative regression coefficient, suggests that birch in single-species groups tend to have wider crowns than those intimately mixed with other species.

The model for the Sitka spruce combined data set builds upon the basic linear relationship between *dbh* and $r_{\max}$. The variables N_{HA} and *M* were selected next in the stepwise process, but were eventually removed in favour of $N_{0.01}$, *Udbh* and *h*. The *d* coefficient associated with *Udbh* is positive, showing a positive relationship between tree dominance and crown width. The coefficients for $N_{0.01}$ and *h* are negative, suggesting that crowns are narrower for trees with more immediate neighbours and for trees that are taller. The negative relationship with height may be driven by the naturally-regenerated spruce in CLG2 and GWY1, which have relatively wide crowns despite their short stature.

Of the many combinations of total crown length model forms and independent variables tested for each data set (see section 3.5.4), the five giving the highest R^2 values for each data set were subjected to full validation; results are shown in Tables 4.25 and 4.26.

Table 4.24 Birch and Sitka spruce maximum crown radius models with spatial variables validation results. Significant biases are marked * (significant at the 0.05 level); *n* indicates data set size (number of trees).

Data set	Model	% Bias	% Accuracy	Efficiency
CYB1 birch (n = 12)	$a+b\cdot dbh+c\cdot Udbh+d\cdot W$	-3.89	63.13	-7.03
CYB2 birch (n = 12)	$a+b\cdot BAL$	12.98*	21.55	0.54
All plots birch (n = 37)	$a+b\cdot Hg_{0.01}+c\cdot M$	-0.61	28.66	0.48
All plots Sitka spruce (n = 77)	$a+b\cdot dbh+c\cdot N_{0.01}+d\cdot Udbh +f\cdot h$	-0.61	14.75	0.82

Validation results may be compared with those in Table 4.16. The models containing spatial variables produce at least one efficiency value greater than those for the existing models for each data set in all cases except for GWY1 birch, where the highest efficiency values are the same. Increases in efficiency of up to 0.15 (CYB1 birch and CYB2 Sitka spruce) are possible with the new models. However, these tables show the tremendous range of models produced and the general lack of overlap between models for different data sets, even within the same species. This makes it impossible to identify widely applicable models, unless those for the combined data sets are considered acceptable. These at least have the advantage that a single parameterisation covers all occurrences of a given species, and they yield validation results comparable to or better than those for individual data sets, except for the considerably better results for GWY1 birch and spruce.

Table 4.25 Birch alternative total crown length model validation results. Significant biases are marked * (significant at the 0.05 level); *n* indicates data set size (number of trees).

Data set	Model	% Bias	% Accuracy	Efficiency
CYB1 birch (n = 12)	$h \cdot e^{-(a \cdot (h/dbh) + b/(BA_{0.01}+1))}$	-8.85	43.08	0.53
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot M)}$	-7.98	44.86	0.49
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Uh+1))}$	-7.94	46.70	0.44
	$h \cdot e^{-a/(BA_{0.01}+1)}$	-8.67	40.82	0.57
	$h \cdot e^{-a/(Udbh+1)}$	-8.87	48.18	0.41
CYB2 birch (n = 12)	$h \cdot e^{-(a \cdot (h/dbh) + b/(M+1))}$	-3.82	21.60	0.33
	$h \cdot e^{-a/(M+1)}$	-4.67	25.49	0.07
	$h \cdot e^{-(a \cdot (h/dbh) + b/(BAL_{HA}+1))}$	-9.76	22.63	0.25
	$h \cdot e^{-(a \cdot (h/dbh) + b/(BAL+1))}$	-28.37*	51.94	-2.97
	$h \cdot e^{-(a \cdot (h/dbh) + b/(BA_{HA}+1))}$	-9.04	21.97	0.30
GWY1 birch (n = 12)	$h \cdot e^{-a/(W+1)}$	2.46	17.70	0.84
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Udbh+1))}$	2.10	17.20	0.85
	$h \cdot e^{-a/(Udbh+1)}$	1.73	17.15	0.85
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Uh+1))}$	0.52	16.67	0.86
	$h \cdot e^{-a/(Uh+1)}$	-0.05	16.68	0.86
All plots birch (n = 37)	$h \cdot e^{-a \cdot BAL}$	4.35	31.40	0.42
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot Hg_{0.01})}$	8.04	28.19	0.53
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Uh+1))}$	6.35	30.33	0.46
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot M)}$	4.87	29.55	0.49
	$h \cdot e^{-(a \cdot (h/dbh) + b/(W+1))}$	5.91	29.58	0.48

Table 4.26 Sitka spruce alternative total crown length model validation results. Significant biases are marked * (significant at the 0.05 level); *n* indicates data set size (number of trees).

Data set	Model	% Bias	% Accuracy	Efficiency
CLG1 Sitka spruce (n = 25)	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot N_{HA})}$	-3.55	14.54	0.68
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Udbh+1))}$	-3.78	14.90	0.66
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BA_{HA})}$	-3.73	16.32	0.60
	$h \cdot e^{-(a \cdot (h/dbh) + b/(Uh+1))}$	-1.86	13.97	0.71
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot Hg_{HA})}$	-3.20	14.23	0.69
CLG2 Sitka spruce (n = 12)	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BA_{0.01})}$	7.50	17.96	0.69
	$h \cdot e^{-(a \cdot (h/dbh) + b/(W+1))}$	8.57	20.32	0.61
	$h \cdot e^{-(a \cdot (h/dbh) + b/(M+1))}$	6.90	18.31	0.68
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot N_{HA})}$	7.08	16.98	0.73
	$h \cdot e^{-a/(W+1)}$	10.15	21.26	0.57
CYB1 Sitka spruce (n = 12)	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot Uh)}$	8.90	18.65	0.58
	$h \cdot e^{-(a \cdot (h/dbh) + b/(M+1))}$	11.78*	19.84	0.52
	$h \cdot e^{-(a \cdot (h/dbh) + b/HDist)}$	10.89*	19.03	0.56
	$h \cdot e^{-a/(M+1)}$	12.92*	20.27	0.50
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot Udbh)}$	11.13*	18.92	0.57
CYB2 Sitka spruce (n = 12)	$h \cdot e^{-a \cdot Hg_{0.01}}$	3.98	14.67	0.57
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot N_{0.01})}$	5.09	14.21	0.59
	$h \cdot e^{-a \cdot N_{0.01}}$	5.48	14.39	0.58
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot Hg_{HA})}$	1.28	14.22	0.60
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot M)}$	2.12	16.87	0.43
GWY1 Sitka spruce (n = 14)	$h \cdot e^{-a \cdot BA_{0.02}}$	-5.35	29.47	0.81
	$h \cdot e^{-a/(M+1)}$	-3.60	19.83	0.91
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot W)}$	12.96	40.48	0.63
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BAL_{HA})}$	1.72	26.19	0.85
	$h \cdot e^{-a \cdot W}$	1.67	37.18	0.69
All plots Sitka spruce (n = 77)	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BAL_{HA})}$	4.79*	21.63	0.67
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BA_{HA})}$	3.26	19.63	0.73
	$h \cdot e^{-(a \cdot (h/dbh) + b/(M+1))}$	1.61	19.33	0.74
	$h \cdot e^{-(a \cdot (h/dbh) + b \cdot BAL)}$	4.85	22.11	0.65
	$h \cdot e^{-(a \cdot (h/dbh) + b/(N_{0.01}+1))}$	2.89	22.19	0.65

These results do show that many spatial variables have the potential to improve crown dimensions predictions based on stem dimensions. Variables incorporated into models for birch are W, M, $Udbh$, Uh, $BA_{0.01}$, BAL, $Hg_{0.01}$ and BAL_{HA}, with M and Uh the most common. For spruce, variables in the tested models are $HDist$, W, M, $Udbh$, Uh, $N_{0.01}$, $BA_{0.01}$, $BA_{0.02}$, BAL, $Hg_{0.01}$, N_{HA}, BA_{HA}, BAL_{HA} and Hg_{HA}, of which W and M are the most common. In 13 of the 20 birch models and 23 of the 30 spruce models, these variables are found in combination with height:diameter ratio. The preponderance of the discrete variables W, M and Uh is interesting, given that their nature might be expected to prevent them from accounting for as much variation as continuous variables. For the birch, species mingling is likely to be related to the transmission of light through neighbouring crowns (although the relationship with L_{total} varies in direction in the models) while height dominance obviously has a bearing on the proportion of the vertical extent of the tree growing free from competition with neighbouring crowns and is positively related to crown length. For spruce, both mingling and the uniform angle index show variation in the direction of their relationships with crown length. A positive relationship between L_{total} and W, as for CLG2 spruce, suggests that an irregular arrangement of neighbours may allow the crown to extend lower down the trunk on the side relatively free from competition, while a negative relationship, as for GWY1 spruce, suggests that a more regular arrangement of neighbours may allow more uniform penetration of light into the stand.

4.5 Crown profile modelling

4.5.1 Crown profile model parameterisation outcomes

Results of simultaneous parameterisations of crown profile models using crown window data for all trees of each species are given in Table 4.27. R^2 values are better for spruce than for birch, and better for light crown models than for shade crown models within each species.

Table 4.27 Birch and Sitka spruce simultaneous crown profile model parameterisation outcomes for crown window sample trees.

		Parameter		
Species	Model	*a*	*b*	R^2
Birch	P1	0.34482	-	0.86362
	P2 (light)	3.51277	-	0.79342
	P3 (light)	0.87411	0.31785	0.86423
	P2 (shade)	2.86575	-	0.65596
	P3 (shade)	1.08446	0.38192	0.74162
	P4	0.42981	-	0.78103
Sitka spruce	P1	0.53782	-	0.96117
	P2 (light)	1.94170	-	0.96257
	P3 (light)	1.45786	0.72755	0.96887
	P2 (shade)	6.15518	-	0.76417
	P3 (shade)	1.84113	0.30264	0.81027
	P4	0.59407	-	0.82662

Results of individual tree parameterisations are shown in Tables 4.28, 4.29 and 4.30. Parameterisations for birch (Table 4.28) show very high R^2 values in the majority of cases. Light crown model R^2 values are relatively poor for tree 429, and model P2 (shade) and P3 (shade) R^2 values are poor for trees 429, 884 and especially 896. R^2 values for model P4 do not reach as high as those for other models but are more consistent than those for P2 (shade) and P3 (shade), ranging between 0.70 and 0.98.

Light crown model parameterisations for spruce (Table 4.29) show excellent R^2 values, particularly for model P3 (light). Outcomes of shade crown model parameterisations (Table 4.30) are considerably poorer; as with birch, model P4 performs more consistently than models P2 (shade) and P3 (shade).

Table 4.28 Birch individual tree crown profile model parameterisation outcomes for crown window sample trees. An asterisk indicates that parameterisation failed to produce a positive R^2 value.

Model	Tree	Parameter *a*	Parameter *b*	R^2
P1	GWY1 tree 131	0.45238	-	0.95806
	GWY1 tree 186	0.42063	-	0.97628
	GWY1 tree 238	0.37638	-	0.95911
	GWY1 tree 429	0.31167	-	0.52183
	GWY1 tree 884	0.38005	-	0.95175
	GWY1 tree 896	0.32354	-	0.94853
P2 (light)	GWY1 tree 131	2.39653	-	0.93427
	GWY1 tree 186	2.57040	-	0.97479
	GWY1 tree 238	2.94094	-	0.98467
	GWY1 tree 429	4.67413	-	0.26968
	GWY1 tree 884	3.02009	-	0.97190
	GWY1 tree 896	3.62389	-	0.94312
P3 (light)	GWY1 tree 131	1.34036	0.56048	0.96339
	GWY1 tree 186	1.67018	0.62235	0.99878
	GWY1 tree 238	2.09311	0.67628	0.99747
	GWY1 tree 429	0.24925	0.16303	0.61311
	GWY1 tree 884	2.07624	0.66703	0.98407
	GWY1 tree 896	1.98621	0.53089	0.97806
P2 (shade)	GWY1 tree 131	2.05102	-	0.96500
	GWY1 tree 186	2.06117	-	0.99490
	GWY1 tree 238	2.92851	-	0.98705
	GWY1 tree 429	2.04044	-	0.20161
	GWY1 tree 884	6.36880	-	0.42592
	GWY1 tree 896	4.18662	-	*
P3 (shade)	GWY1 tree 131	1.34032	0.64680	0.97752
	GWY1 tree 186	2.49451	1.27719	0.99887
	GWY1 tree 238	3.95847	1.50400	0.99483
	GWY1 tree 429	0.50919	0.29069	0.57224
	GWY1 tree 884	1.61137	0.27459	0.68142
	GWY1 tree 896	0.28786	0.13991	*
P4	GWY1 tree 131	0.22968	-	0.86397
	GWY1 tree 186	0.22540	-	0.83160
	GWY1 tree 238	0.34616	-	0.70014
	GWY1 tree 429	0.38431	-	0.97873
	GWY1 tree 884	0.63338	-	0.76447
	GWY1 tree 896	0.57786	-	0.87252

Table 4.29 Sitka spruce individual tree light crown profile model parameterisation outcomes for crown window sample trees.

Model	Tree	Parameter *a*	Parameter *b*	R^2
P1	GWY1 tree 169	0.70189	-	0.96234
	GWY1 tree 170	0.74383	-	0.97943
	GWY1 tree 215	0.47086	-	0.97143
	GWY1 tree 293	0.53821	-	0.96982
	GWY1 tree 300	0.45424	-	0.97840
	GWY1 tree 346	0.59428	-	0.95138
	GWY1 tree 350	0.97950	-	0.99410
	GWY1 tree 468	0.62403	-	0.96969
	GWY1 tree 497	0.43489	-	0.96494
	GWY1 tree 511	0.54833	-	0.99279
	GWY1 tree 573	0.59622	-	0.98408
	GWY1 tree 603	0.40780	-	0.97414
	GWY1 tree 608	0.75984	-	0.99818
	GWY1 tree 609	0.38318	-	0.91063
	GWY1 tree 867	0.35597	-	0.96728
P2 (light)	GWY1 tree 169	1.52772	-	0.99277
	GWY1 tree 170	1.40899	-	0.99809
	GWY1 tree 215	2.27749	-	0.99062
	GWY1 tree 293	1.98906	-	0.99475
	GWY1 tree 300	2.37672	-	0.96643
	GWY1 tree 346	1.82929	-	0.99752
	GWY1 tree 350	1.03765	-	0.99477
	GWY1 tree 468	1.67298	-	0.99294
	GWY1 tree 497	2.54267	-	0.96306
	GWY1 tree 511	1.82972	-	0.95959
	GWY1 tree 573	1.74341	-	0.99527
	GWY1 tree 603	2.69768	-	0.96539
	GWY1 tree 608	1.29946	-	0.99057
	GWY1 tree 609	3.01395	-	0.99895
	GWY1 tree 867	3.22630	-	0.91612
P3 (light)	GWY1 tree 169	1.83691	1.25212	0.99681
	GWY1 tree 170	1.55091	1.12143	0.99931
	GWY1 tree 215	1.76971	0.74848	0.99850
	GWY1 tree 293	1.72430	0.84829	0.99741
	GWY1 tree 300	1.50390	0.61648	0.99352
	GWY1 tree 346	2.06594	1.16441	0.99937
	GWY1 tree 350	1.12800	1.10024	0.99566
	GWY1 tree 468	1.62232	0.96347	0.99307
	GWY1 tree 497	1.63611	0.63042	0.98273
	GWY1 tree 511	1.12962	0.60149	0.99434
	GWY1 tree 573	1.47972	0.82921	0.99887
	GWY1 tree 603	1.64764	0.59146	0.99458
	GWY1 tree 608	1.03550	0.78255	0.99833
	GWY1 tree 609	2.91394	0.95839	0.99908
	GWY1 tree 867	1.51131	0.47288	0.98072

Table 4.30 Sitka spruce individual tree shade crown profile model parameterisation outcomes for crown window sample trees. An asterisk indicates that parameterisation failed to produce a positive R^2 value.

Model	Tree	Parameter *a*	Parameter *b*	R^2
P2 (shade)	GWY1 tree 169	3.30523	-	0.45037
	GWY1 tree 170	8.94945	-	*
	GWY1 tree 215	5.83308	-	*
	GWY1 tree 293	2.84444	-	0.96928
	GWY1 tree 300	19.67970	-	*
	GWY1 tree 346	9.23423	-	0.88907
	GWY1 tree 350	12.14425	-	*
	GWY1 tree 468	6.68388	-	0.47469
	GWY1 tree 497	72.01264	-	*
	GWY1 tree 511	4.09871	-	0.88164
	GWY1 tree 573	4.86656	-	0.86480
	GWY1 tree 603	59.94109	-	*
	GWY1 tree 608	4.78257	-	0.80689
	GWY1 tree 609	10.07539	-	*
	GWY1 tree 867	19.63571	-	*
P3 (shade)	GWY1 tree 169	2.35379	0.00000	0.17597
	GWY1 tree 170	1.34981	0.00000	*
	GWY1 tree 215	8.27363	2.77644	*
	GWY1 tree 293	1.94092	0.64277	0.98420
	GWY1 tree 300	5.20957	0.00000	*
	GWY1 tree 346	2.44822	0.28852	0.96383
	GWY1 tree 350	1.68491	0.11913	*
	GWY1 tree 468	1.88685	0.29696	0.65435
	GWY1 tree 497	5.20979	0.00000	*
	GWY1 tree 511	3.50116	0.82458	0.88304
	GWY1 tree 573	2.10066	0.40821	0.95843
	GWY1 tree 603	0.53996	0.10678	0.53721
	GWY1 tree 608	2.21565	0.41466	0.84991
	GWY1 tree 609	0.68596	0.13171	*
	GWY1 tree 867	0.87225	0.06919	*
P4	GWY1 tree 169	0.48225	-	0.83069
	GWY1 tree 170	0.81614	-	0.80190
	GWY1 tree 215	0.61905	-	0.66776
	GWY1 tree 293	0.32790	-	0.82382
	GWY1 tree 300	0.84884	-	0.41648
	GWY1 tree 346	0.60987	-	0.53453
	GWY1 tree 350	0.75577	-	0.56350
	GWY1 tree 468	0.62000	-	0.73961
	GWY1 tree 497	0.89064	-	0.24110
	GWY1 tree 511	0.48412	-	0.71082
	GWY1 tree 573	0.54799	-	0.70541
	GWY1 tree 603	0.66376	-	0.77007
	GWY1 tree 608	0.53576	-	0.70881
	GWY1 tree 609	0.71352	-	0.97195
	GWY1 tree 867	0.84630	-	0.92670

The rather variable outcomes of parameterisations for models P2 (shade) and P3 (shade) are a consequence of the fact that crown window data often show substantial measurable radius at the crown base. For the birch parameterisation data set, tree 131 has a crown radius of 0.02 m at crown base, tree 186 0.00 m, tree 238 0.02 m, tree 429 1.49 m, tree 884 0.97 m and tree 896 1.47 m. Crown base radii for Sitka spruce range from 0.42 m (tree 350) to 3.57 m (tree 867). Models P2 (shade) and P3 (shade), however, are constructed so that crown radius is always zero at the crown base; hence the poor parameterisation R^2 values for the birches 429, 884 and 896 and for spruce such as 867. Model P4, on the other hand, allows for crown base radius to range between zero and maximum crown radius; this seems to be the most significant factor in producing robust model outcomes.

4.5.2 Sub-model development

Crown profile sub-models were developed using only data from parameterisations yielding positive R^2 values. This meant that all parameter values were used for models P1, P2 (light), P3 (light) and P4, but that some were discarded for models P2 (shade) and P3 (shade). Sub-models were selected from the various forms and independent variables available (see section 3.4.1) on the basis of R^2 following parameterisation. The best sub-models for birch (BI) light crowns all incorporate crown dimensions as independent variables:

(4.1) BI P1 $a = 0.563499640 \cdot r_{\max}^{-0.513482329}$ $R^2 = 0.79655$

(4.2) BI P2 (light) $a = (0.556158562 + r_{\max})^{1.114634207}$ $R^2 = 0.92480$

(4.3) BI P3 (light) $a = 13.977823100 \cdot L_{total}^{-1.377866242}$ $R^2 = 0.85277$

(4.4) BI P3 (light) $b = e^{-0.193746961 \cdot L_{light}}$ $R^2 = 0.91548$

where L_{light} = light crown length (m)
L_{total} = total crown length (m)
$r_{\max}$ = maximum crown radius (m)

The sub-models for the shade crown are based on species mingling, total crown length, and crown ratio:

(4.5) BI P2 (shade) $a = e^{4.512841380\cdot\left(\left(\frac{1}{M+1}\right)-0.389746144\right)}$ $R^2 = 0.95877$

(4.6) BI P3 (shade) $a = e^{11.258882105\cdot\left(\left(\frac{1}{L_{total}}\right)-0.156913531\right)}$ $R^2 = 0.90790$

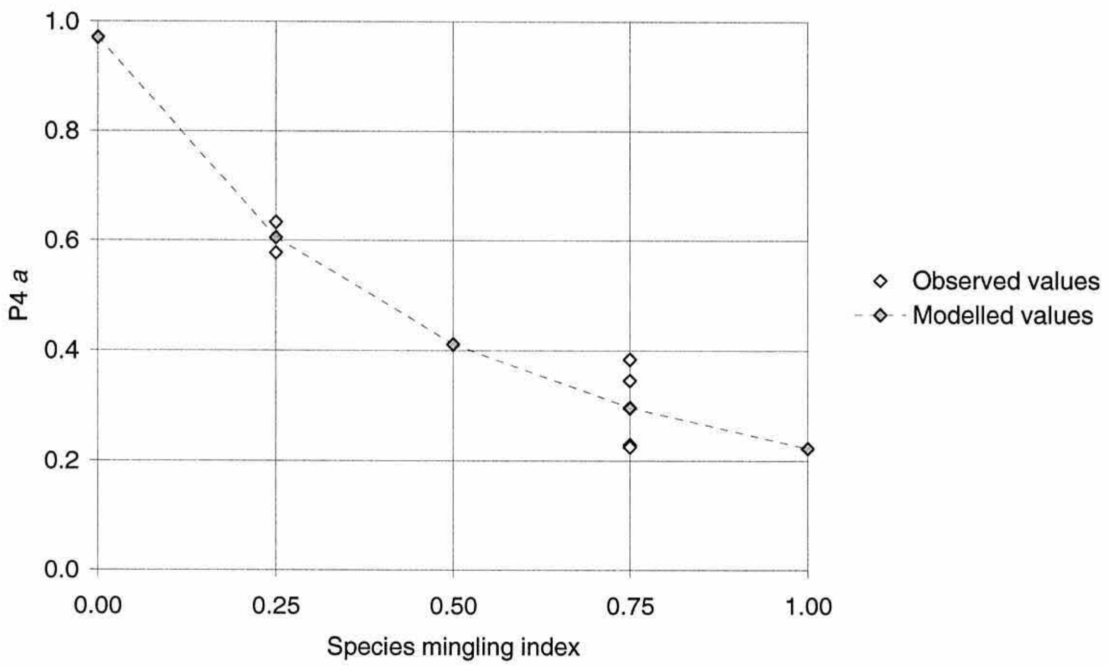
(4.7) BI P3 (shade) $b = e^{-4.272844382\cdot((L_{total}/h)-0.621922796)}$ $R^2 = 0.75205$

(4.8) BI P4 $a = (1.013610701 + M)^{-2.143421202}$ $R^2 = 0.85722$

where h = total height (m)
M = species mingling index

As with alternative crown length models (section 4.4.5), the incorporation of a discrete variable such as species mingling is interesting. Mingling shows very little variation within the birch parameterisation data set; Fig. 4.16 plots observed values of parameter P4 a against species mingling, and also shows sub-model outputs across the full range of potential mingling values.

Fig. 4.16 Observed and modelled P4 *a* parameter values plotted against values of the species mingling index for birch crown window sample trees in the parameterisation data set.



The fact that there is such a limited range of mingling values, with only values of 0.25 and 0.75 represented, may have consequences when sub-models based on this variable are applied to the validation data set, where mingling values range from 0.50 to 1.00.

The Sitka spruce (SS) light crown profile sub-models incorporate stem dimensions, crown dimensions and the basal area of neighbouring trees:

(4.9) SS P1 $a = 0.870880835 \cdot L_{light}^{-0.211784172}$ $R^2 = 0.34716$

(4.10) SS P2 (light) $a = 1.046475260 + 0.350550124 \cdot (L_{light} / r_{\max})$ $R^2 = 0.43859$

(4.11) SS P3 (light) $a = e^{0.008137550 \cdot (BA_{0.01} + 42.08254735)}$ $R^2 = 0.21632$

(4.12) SS P3 (light) $b = 1.258779627 \cdot (h/dbh)^{0.702820384}$ $R^2 = 0.41281$

where $BA_{0.01}$ = basal area of 0.01 ha circular plot ($m^2\ ha^{-1}$)

Both sub-models for model P3 (light) parameters may be viewed in terms of the effects of competition on crown shape: for the *a* parameter, the basal area of neighbours reflects current competition; for the *b* parameter, height:diameter ratio reflects the influence of competition on the subject tree in the past.

Shade crown profile sub-models for spruce are based on crown dimensions and spatial variables:

(4.13) SS P2 (shade) $a = e^{1.866451612 \cdot (W + 0.338152335)}$ $R^2 = 0.66852$

(4.14) SS P3 (shade) $a = 6.231465311 \cdot (L_{total} / r_{\max})^{-0.914847939}$ $R^2 = 0.71530$

(4.15) SS P3 (shade) $b = e^{-7.609019680 \cdot \left(\left(\frac{1}{Uh+1} \right) - 0.432057201 \right)}$ $R^2 = 0.68241$

(4.16) SS P4 $a = e^{-11.177453729 / (BA_{0.02} + 1)}$ $R^2 = 0.12856$

where $BA_{0.02}$ = basal area of 0.02 ha circular plot ($m^2\ ha^{-1}$)
Uh = height dominance index
W = uniform angle index

The indices *Uh* and *W* show greater variation for spruce than species mingling does for birch. Observed and modelled values of the parameters P2 (shade) *a* and P3 (shade) *b* are plotted against the uniform angle index and height dominance index respectively in Figs. 4.17 and 4.18.

Sub-model parameterisation R^2 values are much higher for birch than for Sitka spruce. However, the small sizes of the birch parameterisation and validation data sets may mean that differences arising from the random allocation of sample trees to the groups compromise model performance, as in the example of species mingling above where the ranges of the variable are different in the two data sets.

Fig. 4.17 Observed and modelled P2 (shade) *a* parameter values plotted against values of the uniform angle index for Sitka spruce crown window sample trees in the parameterisation data set.

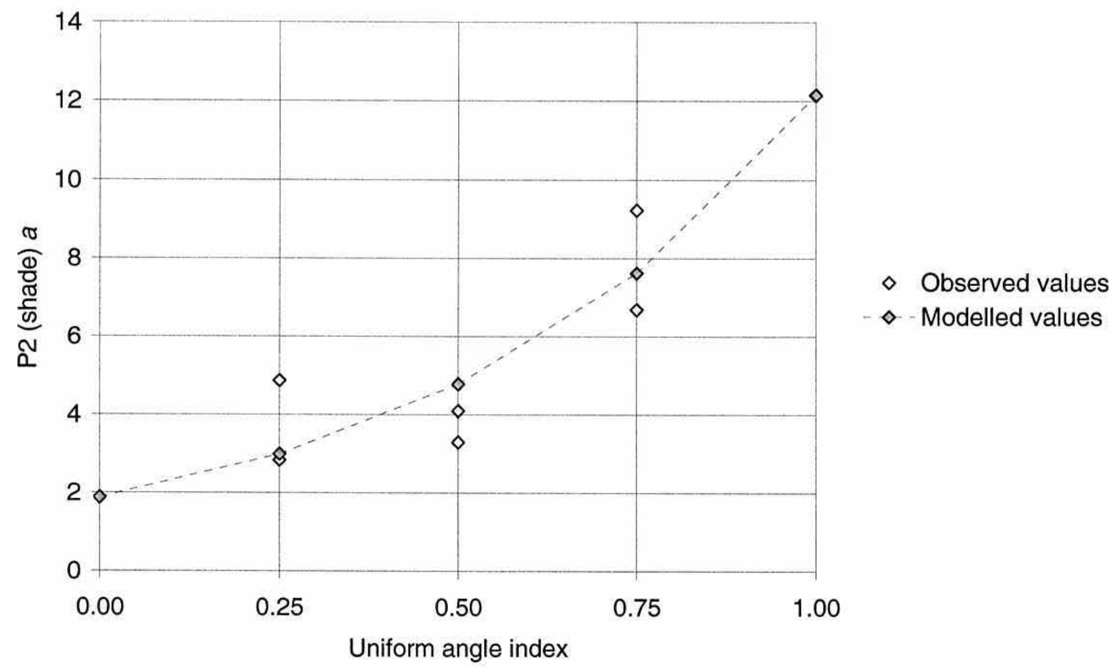
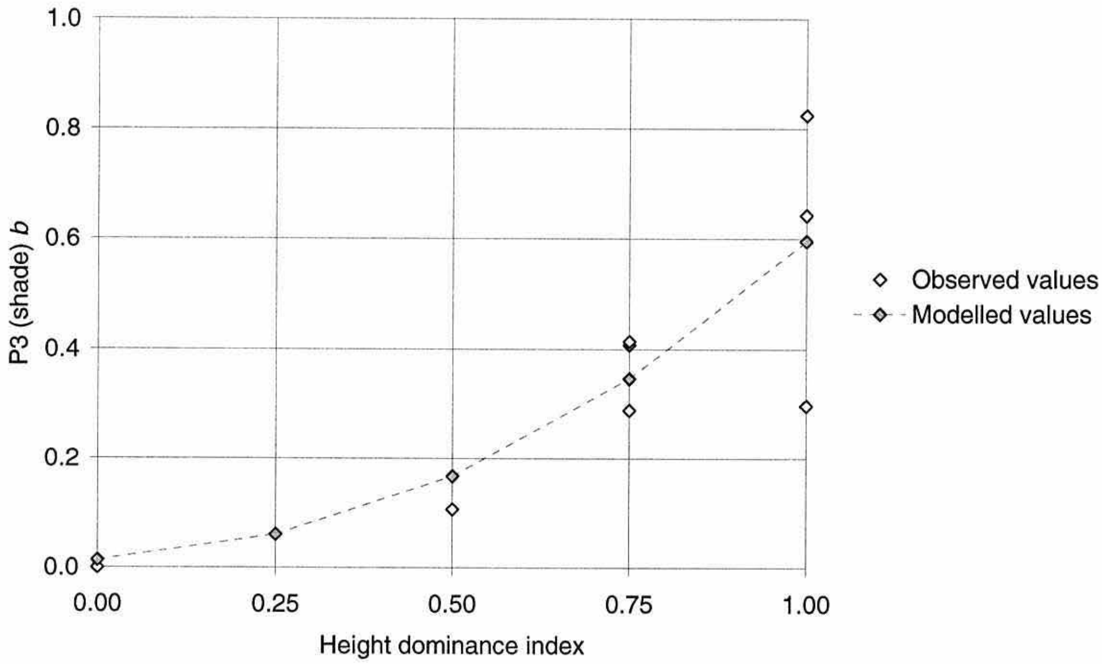


Fig. 4.18 Observed and modelled P3 (shade) *b* parameter values plotted against values of the height dominance index for Sitka spruce crown window sample trees in the parameterisation data set.



4.5.3 Crown profile model validation results

Results of birch crown profile model statistical validations based on simultaneous parameterisation and parameter sub-modelling are shown in Tables 4.31 and 4.32 respectively. Both modelling approaches yield a large proportion of significant biases for light and shade crowns; this may be due to the small sizes of the parameterisation and validation data sets, as noted above. Model efficiencies are generally better for light crown models than for shade crown models, but differences between parameterisation methods are slight. Of the light crown models, P2 (light) shows some lower efficiency values, but results for P1 and P3 (light) are broadly similar. All shade crown models yield a number of negative efficiency values, despite the more robust performance of model P4 during individual tree parameterisations. As with the abundance of significant biases, it may be that, given the outward variability of birch crown shapes, it is only possible to produce reliable profile models with the benefit of larger data sets.

Table 4.31 Birch crown profile model validation results, with simultaneous parameterisation. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked ** (significant at the 0.01 level); *n* indicates data set size (number of light/shade crown profile measurements).

		Model					
Tree	Statistic	P1	P2 light	P3 light	P2 shade	P3 shade	P4
16 (*n* = 28/22)	% Bias	17.00**	22.80**	16.32**	-11.99**	-12.93**	-13.79**
	% Acc.	21.65	25.34	21.71	18.80	16.81	18.76
	Eff.	0.77	0.68	0.77	0.43	0.54	0.43
188 (*n* = 32/18)	% Bias	9.94**	15.33**	9.30**	-14.76**	-15.78**	-16.19**
	% Acc.	13.40	24.29	12.67	24.54	20.59	19.11
	Eff.	0.83	0.44	0.85	-0.80	-0.28	-0.11
256 (*n* = 16/15)	% Bias	-0.54	4.70**	-1.14	0.85	0.37	1.52
	% Acc.	12.75	6.67	13.64	11.89	9.48	22.98
	Eff.	0.91	0.98	0.90	0.93	0.95	0.73
815 (*n* = 19/15)	% Bias	10.80**	16.50**	10.14**	-23.27**	-24.30**	-24.24**
	% Acc.	16.94	17.95	17.27	36.00	32.43	28.01
	Eff.	0.85	0.83	0.85	-20.28	-16.44	-12.18
885 (*n* = 23/7)	% Bias	5.65**	10.97**	5.03**	-8.43	-10.63	-6.64**
	% Acc.	10.32	19.25	9.89	30.09	27.70	7.61
	Eff.	0.91	0.69	0.92	-0.55	-0.33	0.89

Table 4.32 Birch crown profile model validation results, with parameter sub-modelling. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level) or ** (0.01 level); *n* indicates data set size (number of light/shade crown profile measurements).

		Model					
Tree	Statistic	P1	P2 light	P3 light	P2 shade	P3 shade	P4
16 (*n* = 28/22)	% Bias	8.57**	9.66**	13.75**	-25.71**	-10.98**	-26.25**
	% Acc.	12.88	12.76	15.77	31.50	15.76	30.09
	Eff.	0.92	0.92	0.88	-0.63	0.60	-0.49
188 (*n* = 32/18)	% Bias	11.55**	18.59**	3.62*	-27.94**	-16.97**	-28.31**
	% Acc.	14.54	26.00	9.03	35.55	20.30	32.18
	Eff.	0.80	0.36	0.92	-2.83	-0.26	-2.17
256 (*n* = 16/15)	% Bias	-5.15	-2.52	-7.24*	5.52	-11.10**	0.15
	% Acc.	12.69	6.93	12.38	12.25	16.16	22.45
	Eff.	0.91	0.97	0.92	0.92	0.86	0.74
815 (*n* = 19/15)	% Bias	0.44	0.08	17.81**	-27.90**	-12.66	-31.31**
	% Acc.	10.33	9.44	19.55	39.71	27.37	36.28
	Eff.	0.95	0.96	0.80	-25.04	-11.13	-21.10
885 (*n* = 23/7)	% Bias	-8.38**	-10.83*	17.35**	-4.57	8.04	-7.84**
	% Acc.	15.79	23.34	20.79	30.53	37.52	8.99
	Eff.	0.79	0.55	0.63	-0.58	-1.40	0.85

Validation results based on the simultaneous parameterisation of Sitka spruce crown profile models are given in Table 4.33. The light crown models produce far more significant biases than the shade crown models. Of the light crown models, P2 (light) and P3 (light) perform better than P1 in terms of accuracies and efficiencies, but there is little to separate the performance of these two models beyond the fact that P3 (light) produces slightly fewer significantly biased results than P2 (light). In 80 % of cases where all three shade crown models produce positive efficiency values, model P3 (shade) gives the highest. For nine of the 14 trees in the validation data set, however, models P2 (shade) and P3 (shade) give negative efficiencies. In seven of the cases, P4 gives positive efficiencies ranging from 0.20 to 0.99, while in the remaining two it merely produces smaller negative values than P2 (shade) and P3 (shade). Overall, P4 clearly gives the most reliable results for shade crown profile, but there is still considerable scope for improvement in model performance.

Validations of crown profile models with parameter sub-models also result in more significant biases for light crown models than for shade crown models (Table 4.34). Between 11 and 13 of the 14 trees show significant biases for models P1, P2 (light) and P3 (light). Rating performance in terms of accuracy and efficiency, P2 (light) is superior to the other light crown models. Although the shade crown models produce few significant biases, they also produce few positive efficiencies. Only three trees have positive efficiencies for all three shade crown models; model P3 (shade) performs slightly better in these cases. In one case (for tree 337), only model P3 (shade) gives a negative efficiency; here model P2 (shade) performs best. In nine cases, only model P4 gives positive efficiency values, ranging from 0.21 to 0.98. In the remaining case, all three models give negative efficiencies. As with simultaneous parameterisation, model P4 gives the most robust results for the shade crown, but predictive power can still vary widely.

Table 4.33 Sitka spruce crown profile model validation results, with simultaneous parameterisation. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level) or ** (0.01 level); *n* indicates data set size (number of light/shade crown profile measurements).

		Model					
Tree	Statistic	P1	P2 light	P3 light	P2 shade	P3 shade	P4
120 (n = 47/2)	% Bias % Acc. Eff.	-1.22 13.18 0.93	0.31 4.84 0.99	0.42 8.64 0.97	-38.50 66.68 -4.60	-38.50 66.68 -4.60	-1.96 3.39 0.99
121 (n = 48/4)	% Bias % Acc. Eff.	6.23** 9.93 0.96	7.88** 9.66 0.96	7.99** 9.07 0.96	-13.54 42.56 -3.55	-17.55 41.23 -3.38	-5.49 7.28 0.85
157 (n = 38/3)	% Bias % Acc. Eff.	-2.98 13.52 0.93	-1.46* 4.46 0.99	-1.37 8.60 0.97	-14.53 48.62 -1.48	-17.98 46.09 -1.30	2.91 7.03 0.95
263 (n = 23/3)	% Bias % Acc. Eff.	5.75* 11.76 0.95	7.49** 8.32 0.97	7.54** 9.52 0.97	-27.68 62.29 -54.96	-30.60 61.28 -54.44	-12.93 18.72 -4.70
296 (n = 31/8)	% Bias % Acc. Eff.	10.59** 23.29 0.86	12.35** 17.50 0.92	12.43** 20.47 0.89	-1.10 23.44 0.29	-4.73 22.25 0.36	-2.22 13.61 0.76
337 (n = 30/20)	% Bias % Acc. Eff.	6.93** 11.72 0.95	8.63** 10.49 0.96	8.71** 10.62 0.95	-4.49 11.54 0.76	-6.55** 10.36 0.80	-8.74* 18.51 0.37
378 (n = 18/16)	% Bias % Acc. Eff.	13.88** 21.44 0.87	15.83** 19.65 0.89	15.84** 20.63 0.88	-3.68 26.73 -5.17	-6.32 22.79 -3.50	-8.13** 9.40 0.20
446 (n = 38/13)	% Bias % Acc. Eff.	-12.49** 15.60 0.84	-11.12** 13.69 0.87	-11.04** 13.33 0.88	8.19 20.41 0.62	6.34 14.72 0.80	6.62 18.04 0.70
466 (n = 27/18)	% Bias % Acc. Eff.	-10.81** 12.76 0.88	-9.37** 14.49 0.84	-9.31** 12.28 0.89	-8.86 23.67 -3.47	-10.86* 19.88 -2.18	-12.61** 14.80 -0.81
531 (n = 28/5)	% Bias % Acc. Eff.	-4.64* 11.52 0.94	-3.11** 3.81 0.99	-3.04* 6.66 0.98	-12.30 27.61 -0.25	-16.21 28.15 -0.34	-8.41 16.62 0.54
545 (n = 37/12)	% Bias % Acc. Eff.	-4.46** 8.29 0.96	-2.96** 4.74 0.99	-2.87** 4.12 0.99	0.31 12.73 0.78	-2.75 11.10 0.83	-3.25 15.23 0.69
561 (n = 23/6)	% Bias % Acc. Eff.	-0.27 11.05 0.95	1.37* 2.84 1.00	1.42 6.51 0.98	7.63 16.58 0.87	3.15 12.38 0.93	9.51 31.31 0.55
584 (n = 24/14)	% Bias % Acc. Eff.	-5.43** 8.68 0.96	-3.88** 6.79 0.98	-3.83** 5.61 0.98	1.53 26.23 -0.90	-0.63 21.33 -0.26	-1.27 3.48 0.97
590 (n = 32/18)	% Bias % Acc. Eff.	-3.11** 6.79 0.97	-1.58 7.69 0.97	-1.50 5.14 0.99	-8.30 20.84 -0.68	-9.90* 17.73 -0.23	-11.18** 13.67 0.26

Table 4.34 Sitka spruce crown profile model validation results, with parameter sub-modelling. Values in each cell are relative bias (%), relative accuracy (%) and efficiency. Significant biases are marked * (significant at the 0.05 level) or ** (0.01 level); *n* indicates data set size (number of light/shade crown profile measurements).

		Model					
Tree	Statistic	P1	P2 light	P3 light	P2 shade	P3 shade	P4
120 (*n* = 47/2)	% Bias	-6.70**	4.51**	-0.40	-38.50	-38.50	-2.91
	% Acc.	13.39	7.53	6.49	66.68	66.68	5.03
	Eff.	0.93	0.98	0.98	-4.60	-4.60	0.97
121 (*n* = 48/4)	% Bias	0.50	12.39**	1.78**	-15.49	-14.49	1.52
	% Acc.	5.56	14.40	4.46	41.74	42.22	7.05
	Eff.	0.99	0.91	0.99	-3.43	-3.51	0.88
157 (*n* = 38/3)	% Bias	-9.93**	-0.49	-10.32**	-15.49	-14.05	-0.87
	% Acc.	15.54	4.04	12.88	47.83	49.04	4.16
	Eff.	0.90	0.99	0.93	-1.42	-1.51	0.98
263 (*n* = 23/3)	% Bias	-5.82**	1.79**	9.54**	-31.73	-27.21	-2.73
	% Acc.	9.02	2.11	10.86	61.04	62.50	4.41
	Eff.	0.97	1.00	0.96	-54.51	-55.13	0.70
296 (*n* = 31/8)	% Bias	0.95	6.75**	13.62**	4.72	6.99	8.69
	% Acc.	16.94	12.81	18.92	29.45	33.19	21.01
	Eff.	0.92	0.96	0.90	-0.12	-0.43	0.42
337 (*n* = 30/20)	% Bias	8.25**	12.80**	9.47**	-8.08*	-23.37**	-7.90*
	% Acc.	12.95	14.49	11.22	15.39	28.90	18.20
	Eff.	0.93	0.92	0.95	0.56	-0.57	0.39
378 (*n* = 18/16)	% Bias	-0.61	6.27**	16.96**	-7.22	5.69	-5.75**
	% Acc.	9.95	9.55	21.29	28.03	24.75	6.70
	Eff.	0.97	0.97	0.87	-5.81	-4.30	0.59
446 (*n* = 38/13)	% Bias	-9.89**	-8.84**	-12.05**	4.16	-6.51*	16.91*
	% Acc.	13.50	11.16	14.42	17.77	12.34	28.13
	Eff.	0.88	0.92	0.86	0.72	0.86	0.27
466 (*n* = 27/18)	% Bias	-10.39**	-6.13**	-5.48**	-30.12**	-16.54**	-7.54**
	% Acc.	12.32	11.77	8.89	40.31	24.08	9.83
	Eff.	0.89	0.90	0.94	-12.28	-3.72	0.21
531 (*n* = 28/5)	% Bias	-13.68**	-4.21**	-14.32**	-21.01	-8.34	-1.25
	% Acc.	16.87	5.02	16.42	31.64	28.92	16.39
	Eff.	0.87	0.99	0.88	-0.73	-0.33	0.58
545 (*n* = 37/12)	% Bias	-3.75**	-5.29**	-6.38**	-11.73*	-8.04*	2.52
	% Acc.	8.06	6.98	7.58	17.96	13.04	17.39
	Eff.	0.97	0.97	0.97	0.55	0.76	0.59
561 (*n* = 23/6)	% Bias	-11.18**	-7.47**	8.40**	4.33	14.29	19.18
	% Acc.	15.03	9.86	11.17	11.69	29.72	40.35
	Eff.	0.91	0.96	0.95	0.94	0.59	0.24
584 (*n* = 24/14)	% Bias	-7.75**	-1.46	-4.37**	4.23	11.27	5.74*
	% Acc.	10.35	4.91	6.29	26.82	29.21	9.20
	Eff.	0.94	0.99	0.98	-0.99	-1.38	0.76
590 (*n* = 32/18)	% Bias	-6.29**	-4.34**	-7.86**	-11.74*	-9.90*	-19.01**
	% Acc.	8.94	9.32	11.19	22.98	18.01	21.26
	Eff.	0.95	0.95	0.93	-1.05	-0.26	-0.81

5 DISCUSSION & CONCLUSIONS

For the convenience of the reader, rather than referring to an exhaustive array of visualisations of the behaviour of the full range of crown dimension and profile models tested, sections 5.3, 5.4 and 5.5 make use of figures within the text to illustrate model behaviour only in key cases.

5.1 Suitability of data collection techniques

5.1.1 Crown survey fieldwork

In most cases, the crown survey fieldwork protocol (Appendix I) was followed without difficulty. Sitka spruce crown radius measurements presented no particular problems. As is often the case with crown base measurements (Maguire and Hann, 1987; Short and Burkhart, 1992), however, there was some subjectivity in the identification of spruce crown bases, mostly in identifying "sparsely foliated branches not contiguous with the main part of the crown".

Measurements of the crowns of the heavily suppressed birch sample trees in plots CYB1 and CYB2 were more complicated than those of the relatively vigorous birch trees in GWY1. As noted in section 4.1.2, many of the trees were leaning heavily. Three of the sample trees in CYB2 with extremely bent or leaning stems were replaced with other randomly selected trees, but other leaning trees were retained in the sample because of the limited number of potential replacements. The greatest effect of heavily leaning stems was on crown radius measurements. These were taken from the breast height point, as this was the position at which each tree was mapped, but this meant that leaning trees often had relatively few measurable radii. The crown radius measurement methods used were clearly not suitable for these trees (the problems associated with the radius data for these trees are discussed in section 5.2). An alternative approach might be to measure crown radii from a location other than the breast height point of the stem and to relate stem and crown positions using a method such as the crown vector described by Umeki (1995). This would also entail a more sophisticated approach to crown modelling; even if crowns were still assumed to be radially symmetrical, it would be necessary to account for variation in crown vectors.

Vertical measurements of crown base height and total height were also affected by leaning stems. In addition, live foliage was often absent from most of the length of branches of suppressed birch because of heavy side shade. In this study, the base of the lowest live branch was taken to represent the crown base of both spruce and birch to avoid subjectivity as far as possible during measurements, but this meant that the measured crown length did not necessarily correspond with the actual vertical extent of foliage. Ward (1964) suggested that the "general level where the leaf surface began" should be taken as the crown base of broadleaved trees, and there may be some justification in adopting this definition of the crown base for birch provided that measurements remain objective.

Problems with visibility meant that only single measurements of total height and height to crown base were made for CYB1 birch, some CYB2 birch, GWY1 birch and GWY1 overstorey spruce. This was not considered to be a major drawback for the relatively straight-stemmed trees in plot GWY1, but almost certainly exacerbated problems with height measurements for the often leaning trees in Coed y Brenin.

5.1.2 Crown window fieldwork and analysis

Crown window fieldwork presented its own set of difficulties. Immediately apparent in the case of birch was the difficulty of finding sample trees with sufficiently good crown visibility, with the entire crown outline visible from two directions separated by 90°. Non-random sampling on the basis of visibility meant that only isolated trees or trees on the edges of patches of regeneration were assessed, and that no crown shape information was gathered for trees within dense areas of regeneration where crown shapes and levels of competition were likely to be very different. The only way to overcome this problem and facilitate fully random sampling of trees growing under a wide range of conditions would be to remove the neighbours of sample trees to improve visibility. This sort of destructive sampling was not considered appropriate in GWY1, as the permanent sample plot was required to provide data for many other aspects of growth modelling.

Drawing crown outlines onto acetates, rather than measuring multiple crown widths in the field, maximised the efficiency of fieldwork (Hussein *et al.*, 2000). By minimising the length of time spent viewing each tree, this also reduced the possibility of the operator's head moving during assessments. High light levels were generally best for the identification of the crown margin, but did lead to problems with reflections on the surface of the crown window; these were overcome by hanging a coat over the operator's head and the top of the crown window to block out any light from behind. To ensure proper orientation and scaling, it was important to identify the crown tip and base clearly on each crown window image.

Methods for the analysis of scanned crown images worked well. If necessary, images were rotated in Paint Shop Pro 7 so that the crown tip was always vertically above the crown base. When producing world files (see section 3.1.4), it was found to be necessary to enter pixel widths (in metres per pixel) to five decimal places to ensure perfect correspondence between measured crown lengths and the lengths of scaled profiles in ArcView. Crown radius measurements in ArcView were carried out without difficulty, although with up to fifty measurements per half profile and four half profiles per tree the process could be time-consuming; the speed of processing would be increased greatly if the crown outline could be identified and measured automatically.

5.1.3 Photogrammetry fieldwork and analysis

In the early stages of the development of a photogrammetry fieldwork protocol (section 3.2.2), difficulties encountered during analysis were addressed by altering the angles between camera stations and experimenting with various aids to referencing, model orientation and scaling. When GWY1 understorey trees were first photographed with 45° camera station intervals, it proved difficult to reference enough points with sufficient confidence to allow early processing, which slowed modelling. This prompted a change to 30° intervals in CLG2 and CLG3. Where the regular spacing of camera stations was possible referencing was found to be easier, but any gaps or irregularities in the arrangement of stations caused by obscuring vegetation could slow analysis or even prevent the modelling of portions of the crown entirely. Where angles were too small processing became less accurate (Eos Systems Inc., 2003, p. 71), and where angles were too large referencing became more difficult. Re-photographing the GWY1 trees with

30° angles between camera stations and two ranging rods to provide easily recognisable points greatly aided early referencing and processing, but gaps in photograph coverage still impeded modelling.

A number of problems arose at various points during photogrammetric analysis of understorey trees:

1. Intervening foliage obscured the crown.
2. There was poor lighting or contrast with the background.
3. Differences in above- and below-canopy light conditions meant that upper whorls were bleached out and blurred in long exposures.
4. Branch tips were difficult to identify accurately in photographs taken shortly after bud burst.
5. Branch tips were difficult to identify in the crowns of suppressed trees with little lateral branch growth in lower whorls.
6. Whorl and interwhorl branches were difficult to distinguish.
7. Other crowns and vegetation limited horizontal viewing distance resulting in unfavourable vertical viewing angles, complicating the interpretation of crown structure. In particular, the normally easily referenced branch tips in the highest whorls were hidden.
8. Unlevelled ranging rods or the crown tip and Vertex transponder did not provide a perfect vertical axis for model orientation.

Many problems occurred simply because surrounding vegetation affected visibility. Sample trees growing in relatively open conditions were selected for the comparison of crown profile assessment methods (section 3.2.3), but in situations where crown data were needed for trees growing, for example, in dense patches of regeneration, it would be necessary to clear surrounding trees to around one tree height distance. Some problems would remain, for example limited lateral growth making branch tips less obvious.

With overstorey trees in CLG1, as with the understorey trees in GWY1, CLG2 and CLG3, horizontal and vertical viewing angles were limited by surrounding crowns. The upper branches most readily used for early referencing were obscured or bleached out and blurred in long exposures. These problems were particularly acute with these larger, fifty-year-old trees, where the density of foliage and structural complexity of older branches made branch tip identification and referencing in lower whorls more difficult. High crown bases (8.5-13.6 m) with long, branchless stems below rendered early referencing aids such as ranging rods all but useless, as any photograph encompassing both the crown and the base of the stem showed too little detail. Analyses of these crowns were eventually abandoned.

In the Clocaenog shelterwood strip CLGS, a target camera station interval of 30° was set in an attempt to alleviate the referencing problems encountered in CLG1. Even in such open conditions, however, this horizontal arrangement of stations was only made possible by compromising on viewing distances and vertical angles, and this, in combination with foliage density and branch complexity, meant that referencing was only possible for the first two to three whorls of each tree, and that 3-D models could not be processed. To overcome these problems, trees were re-photographed from the greatest possible distances using the telephoto zoom, compromising on angles between camera stations. Even so, it was rarely possible to achieve a viewing distance which allowed the entire crown to fit into a single image at maximum telephoto zoom, and it was often necessary to take a series of overlapping photographs at each location. Referencing was easier and extended further down the crown, though not to the crown base, making scaling impossible. In the lower crown difficulties arose because often insufficient overlap had been kept between vertically separated photographs.

Fully developed photogrammetry fieldwork techniques, as described in Appendix I, produced excellent photographs for analysis of small spruce crowns. Although ranging rods could take some time to level accurately, they were invaluable for the scaling, orientation and early processing of 3-D models, and obviated the need for 30° camera station intervals. Difficulties with birch crowns and large spruce crowns seemed to be less to do with fieldwork techniques and more to do with the overall limitations of the photogrammetric approach (principally the need for many recognisable reference points).

Photogrammetric measurements in PhotoModeler Pro 5 were easily taken from small spruce crowns. The reduction of detailed 3-D maps of branch tips to generalised crown profiles for the three individual sample trees in CYB3 was accomplished by calculating a mean branch tip per whorl (see section 3.2.4). However, there are potential problems associated with this method. The most obvious problem arises if whorls cannot be identified, and in such cases it may be necessary to fit crown profile models using raw branch tip data. This is a viable approach, and it would be possible to parameterise models using raw crown window data for comparison, but a method for defining the point of maximum crown radius would be required. It may be too simplistic to use the branch tip with the greatest horizontal reach to define maximum crown radius and light crown length, particularly if the branch tip in question is clearly an outlier. Fitting models to raw data may be the only option for trees whose branches are not arranged in whorls. Incomplete whorls also pose difficulties for the mean branch tip method. If, as in this study, crowns are being modelled as radially symmetrical shapes, the radius of the mean branch tip may be calculated using only remaining branch tips, or remaining branch tips and a number of zero values equal to the branches missing from the whorl. The latter approach may give a better indication of the overall bulk of the whorl, but it may not always be possible to estimate accurately the number of missing branches, and it may be an unnecessary complication to consider the effect of one missing branch in a whorl where six branches remain, for example.

5.2 Suitability of data

The nature of the crown data collected during this study imposed some limitations on modelling. Of particular importance was the fact that data were only available for one time period. It was not feasible to repeat crown measurements during the course of this study as changes in crown dimensions may have been no greater in magnitude than errors in measurements. The scheduled five year remeasurement interval for the *Tyfiant Coed* permanent sample plots, set for the same reason, limited the availability of spatial data. The absence of crown dimension increment data effectively precluded the adoption of dynamic approaches to modelling crown length and width, and meant that only static modelling was possible; the drawbacks of static modelling, particularly of crown length, are discussed in section 5.3. Photogrammetric crown reconstruction (see sections 3.2.4 and 4.3.4) can provide crown shape data for multiple time periods, but these data must be treated with some caution as it is not possible to reconstruct past branch angles with any certainty.

An issue which may have affected modelling using spatial variables, including crown profile model parameter sub-modelling, was the delay between sample plot inventories and crown survey fieldwork. This delay was particularly pronounced for plot GWY1, where some two and a half growing seasons had passed between plot establishment and the survey of birch and spruce crowns. Consequently, there was, on average, a 26 % increase in *dbh* between December 2001 and May-June 2004 for the GWY1 Sitka spruce sample trees and a 14 % increase between December 2001 and August 2004 for the birch. All spatial variables were calculated using the original inventory data (including original *dbh* and height measurements for sample trees). This meant that model tests were carried out using contemporaneous stem and crown data, but older data on stand structure and competition. The significance of this discrepancy depends on the rate of change in relationships between neighbouring trees and on the rate of response of crown dimensions to such changes; these rates are likely to depend on stand structure and species. Current crown dimensions are determined not only by the current competitive status of a tree but also by past competition (Hasenauer and Monserud, 1996), so it would be instructive to test spatial variables from a range of previous time periods as potential predictors of crown size and shape.

It was noted in section 5.1.1 that the maximum crown radius measurement protocol was not suitable for birch trees with extremely asymmetric crowns. There is evidence to suggest that data from these trees are unsuitable for the modelling approach taken in this study; CYB1 and CYB2 birch, which have mean coefficients of variation of maximum crown radius (Table 4.4) and mean relative canopy displacements (Table 4.5) greater than 0.5, show exceptionally poor r_{max} model validation results (Table 4.14), producing negative efficiency values in the majority of cases. In future studies, there may be merit in using these measures of crown shape regularity and displacement to determine when a more sophisticated modelling approach is required.

The discrete spatial variables species mingling, diameter dominance, height dominance and uniform angle index, and to a lesser extent numbers of neighbouring trees, were theoretically less than ideally suited for inclusion in crown models because predictions based upon them would also occur in discrete steps. Despite this, these variables were found to have significant roles in both crown dimension and crown profile modelling (see sections 4.4.5 and 4.5.2). Many spatial variables were closely correlated with overall tree size (*dbh* and height) and so contributed negligible additional predictive power to models.

These considerations aside, crown and spatial data were found to be well suited to crown dimension and profile modelling; this is borne out by the robust modelling results for most data sets.

5.3 Crown dimension models

The choice of crown dimension models for the *Tyfiant Coed* growth model depends primarily on model performance (in terms of statistical validation results) and behaviour (in terms of biological realism), although other aspects, such as simplicity, may also be significant. Crown dimension model performances varied greatly. In general, parameterisations for spruce yielded better results than those for birch, perhaps because of the monopodial growth of spruce. Light crown length models performed better than total crown length models, which tended to perform better than maximum crown radius models, although the exceptional performance of light crown length models may be due to the fact that they were parameterised for GWY1; with its exceptionally wide range of tree dimensions and strong relationships between stem and crown dimensions, the Gwydyr plot data tended to produce the best validation results for all models.

In the context of static modelling, realistic model behaviour may be defined relatively simply. Maximum crown radius models should not produce estimates equal to or less than zero within the likely range of independent variables. As the crown base is defined by the base of a branch, crown length should not exceed tree total height and should not be less than zero; this behaviour is guaranteed by the construction of models L1-4 and models based on spatial variables, and is independent of the values of input variables. Similarly, the construction of light crown length models is such that output values range between zero and total crown length. In the absence of dynamic models, however, these static models will be used to predict crown dimensions for successive time steps. Biological realism becomes a more complex matter in this case. A relatively wide range of maximum crown radius model behaviour may be tolerated because, although crown width generally increases as a tree grows, it may also decrease in some circumstances (Oliver and Larson, 1996; Rudnicki *et al.*, 2004); a dynamic model explicitly accounting for contact with neighbouring crowns (e.g. Pretzsch, 1992) would be needed to predict changes in crown width precisely. Realistic crown length model behaviour depends more on changes in height to crown base with time than on total crown length, as the definition of the crown base is such that *hcb* cannot decrease with time. In this respect, it would be better to predict height to crown base from *dbh* or height than to predict total crown length, but, as noted in section 3.3.1, crown length models were favoured in this study because of their superior predictive power. Specific examples of crown length model behaviours are given in the section 5.3.2. Little information is available on changes in light crown length with time; long-term studies would be required to identify suitable patterns of model behaviour.

In the following sections, maximum crown radius, total crown length and light crown length models are discussed and recommendations are made concerning the model forms best suited to the purposes of the *Tyfiant Coed* growth model, with the proviso that caution must be exercised in applying these models outwith the range of parameterisation data.

5.3.1 Maximum crown radius models

Only data from GWY1 birch sample trees proved to be amenable to maximum crown radius modelling using models R1-7 (see section 5.2). For this data set, the models based on tree total height (R2 and R6) performed relatively poorly in statistical validations (Table 4.14). Model R4 gave the highest model efficiency (0.65) and the lowest bias (2.17 %), followed by R3 (efficiency 0.55, bias 2.98 %), suggesting that *dbh* alone is an adequate predictor of crown radius. The behaviour of these two models is plotted in Fig. 5.1. Within the range of raw data the models show very similar behaviour, but extrapolating beyond this range leads to considerable differences in predictions, and in many cases the downwards trend in crown radius predicted by model R4 beyond 18 cm *dbh* may be less realistic than the upwards trend of model R3.

Fig. 5.1 Behaviour of maximum crown radius models R3 and R4 parameterised for GWY1 crown survey birch, showing observed and modelled maximum crown radius plotted against diameter at breast height.

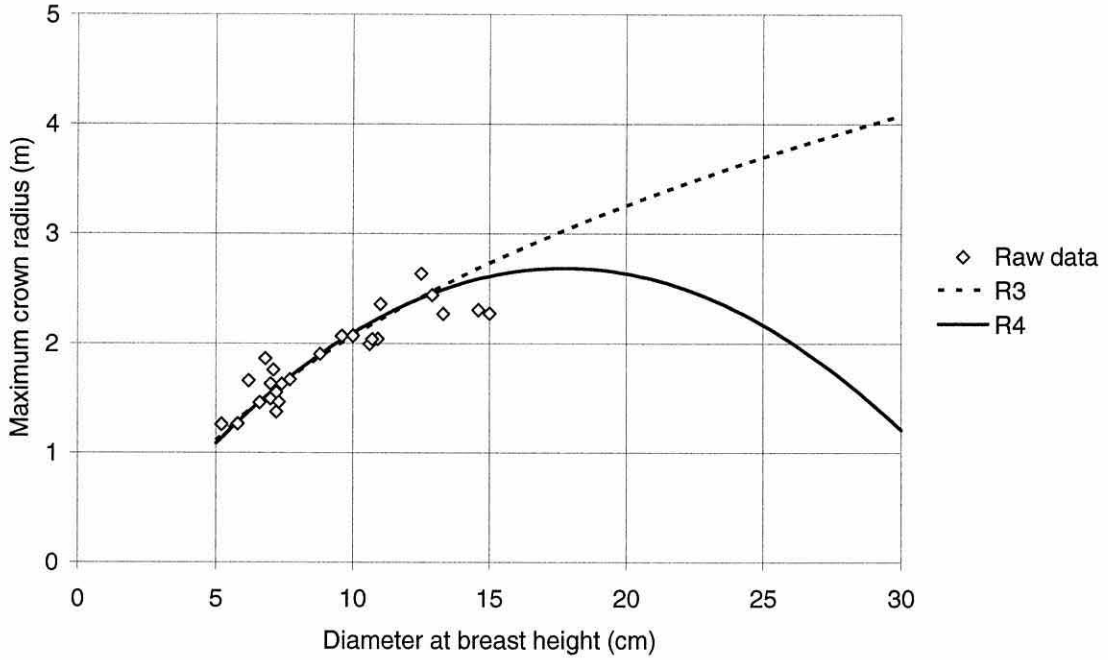
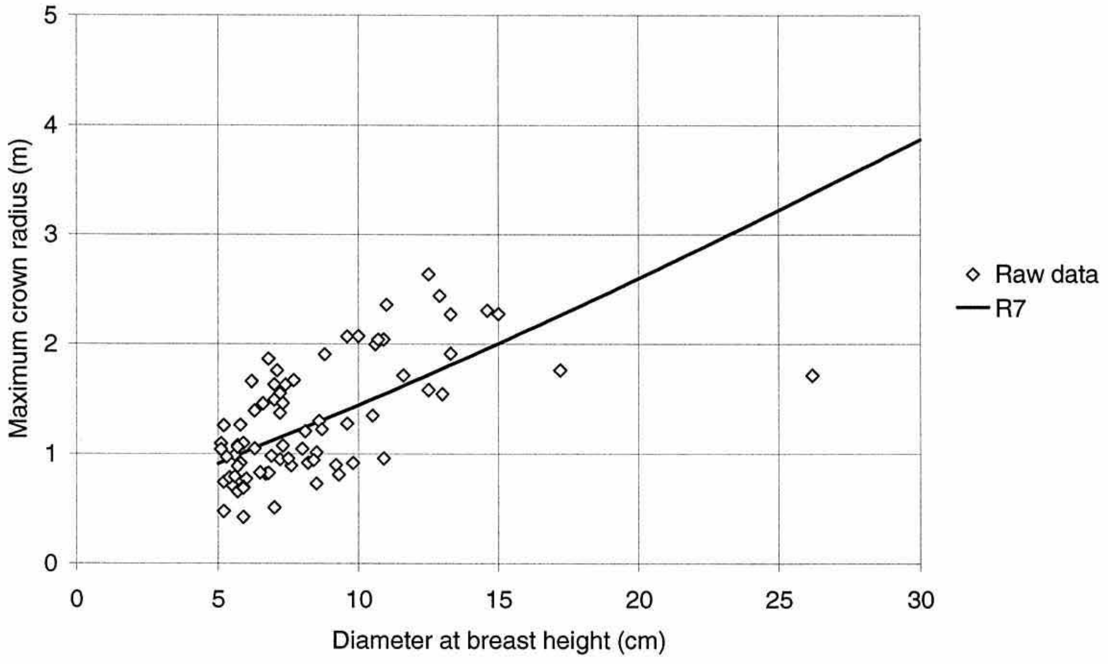


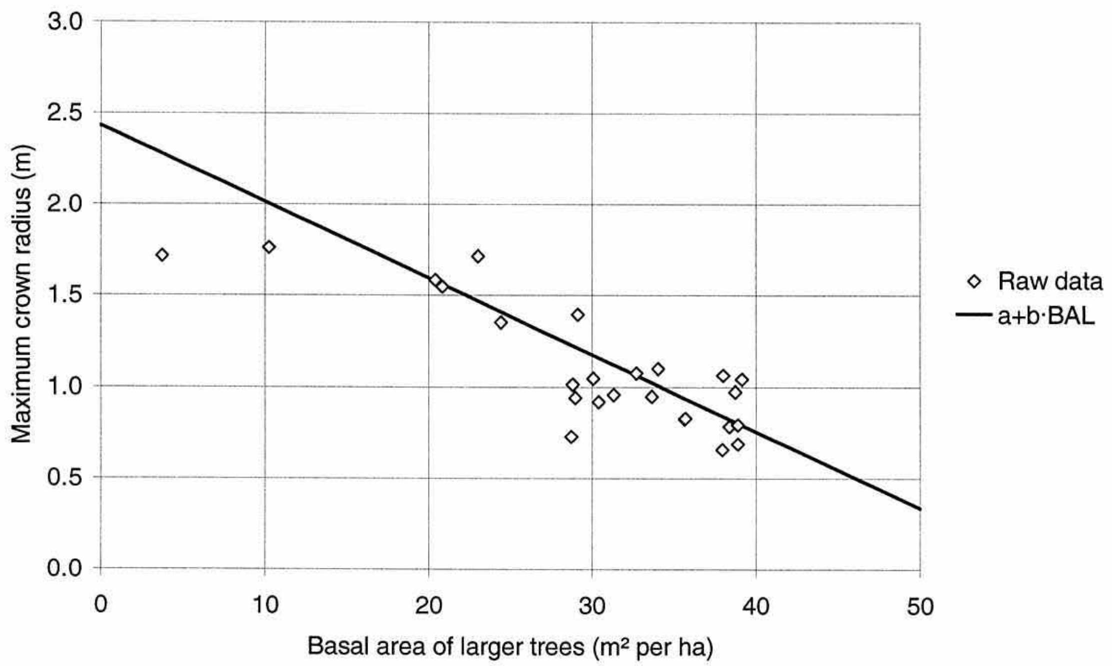
Fig. 5.2 Behaviour of maximum crown radius model R7 parameterised for all crown survey birch, showing observed and modelled maximum crown radius plotted against diameter at breast height.



Despite the failings of the Coed y Brenin data, some good validation results were achieved for the data set combining CYB1, CYB2 and GWY1 data, with model R7 performing particularly well (efficiency 0.63, bias 2.72 %). Stepwise linear regressions using spatial variables (Table 4.24) failed to improve on these values. The upwards trend of predictions from R7 (Fig. 5.2) is, if anything, less strong than that in the raw data, but it is difficult to judge how realistic extrapolations may be because of the regrettable paucity of data between 15 and 25 cm *dbh*. The outlier at 26.2 cm *dbh* was in the validation data set and so did not influence model fitting.

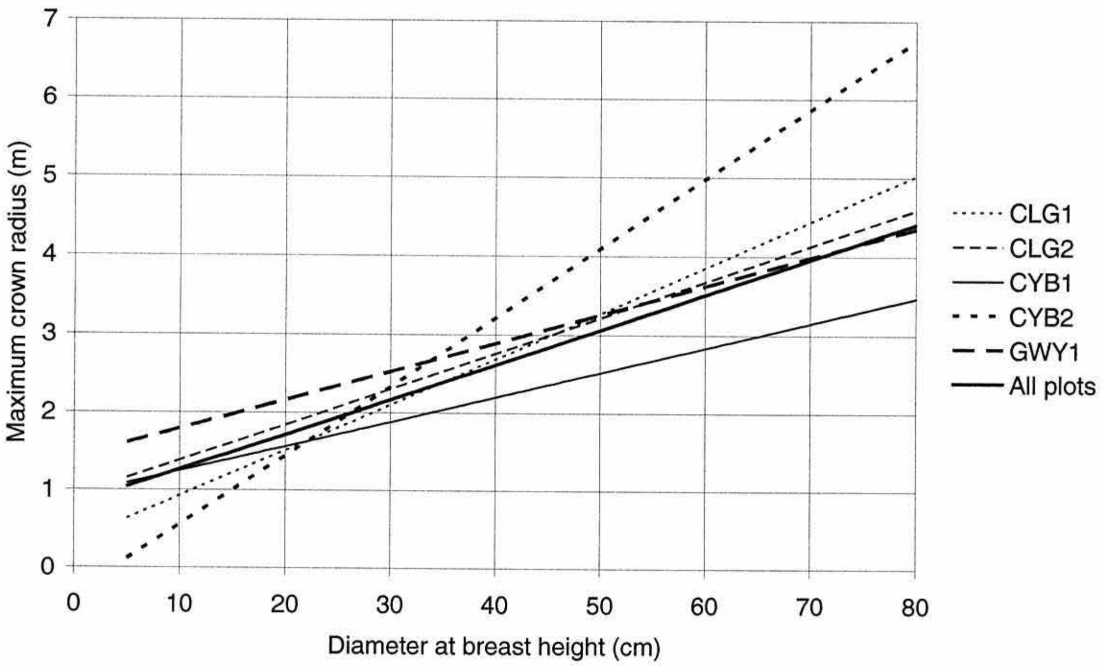
The model derived by stepwise regression for CYB2, incorporating the basal area of larger trees, performed relatively well (efficiency 0.54, bias 12.98 % significant at the 0.05 level). Although this linear relationship (Fig. 5.3) can produce negative crown radius values for small trees in exceptionally dense stands, this could be seen as a positive attribute of the model; reduction below a critical threshold value of r_{max} during a modelling time step could be taken as an indication of tree mortality. Basal area of larger trees, as a measure of relative tree size, may merit further investigation as a predictor of crown radius and mortality in conjunction with an absolute measure of tree size such as diameter at breast height.

Fig. 5.3 Behaviour of a novel maximum crown radius model parameterised for CYB2 crown survey birch, showing observed and modelled maximum crown radius plotted against diameter at breast height.



Validation results for models R1-7 using Sitka spruce data (Table 4.15) show that the models based solely on tree total height, R2 and R6, performed more poorly than the other models in almost all cases, the only exception being the CYB1 data set. Within each data set, however, there was little difference in performance between the remaining models. Under these circumstances, it seems reasonable to adopt the most basic model, R1, for the sake of simplicity and parameter parsimony. The behaviour of this model for each data set is plotted in Fig. 5.4. The slope of the linear relationship between diameter at breast height and maximum crown radius is similar for most data sets apart from CYB2, where r_{max} is close to zero (0.12 m) at 5 cm *dbh*. Stem diameters in the validation data set for this plot ranged between 12.9 and 30.1 cm, and extrapolations beyond this range should be viewed with caution.

Fig. 5.4 Behaviour of maximum crown radius model R1 parameterised for Sitka spruce, showing modelled maximum crown radius plotted against diameter at breast height for each crown survey data set.



The only novel model produced for spruce by stepwise linear regression was for the combined data set (Table 4.24). In terms of efficiency (0.82) and accuracy (14.75 %), this model performed better than parameterisations of R1-7 for the same data set, and the relative bias (-0.61 %) was smaller than those of all other models except R7. Model behaviour at various values of $N_{0.01}$ and *Udbh* is plotted in Figs. 5.5 and 5.6

respectively. All else being equal, the upwards curve of crown radius with *dbh* is determined by the Prodan (1951) height curve (see section 3.4.2). Fig. 5.5 shows that crown radius decreases as local stocking, represented by the number of stems per hectare in a 0.01 ha circular plot centred on the subject tree, increases. As the diameter dominance of the subject tree increases, however, crown radius also increases, as shown in Fig. 5.6. The overall behaviour of this model appears to be robust. Even with a *Udbh* value of zero and local stocking as high as 4000 stems per hectare, a positive crown radius is produced at 5 cm *dbh*; conversely, if *Udbh* = 1 and $N_{0.01} = 0$, maximum crown radius reaches a realistic value of 4.50 m at 80 cm *dbh*, equal to the largest measured radius in GWY1.

In situations where it is possible to parameterise crown models for each stand to be modelled, it is possible to recommend model R1 for spruce and, tentatively, to recommend model R4 for birch. Where this is not possible, and where a single model parameterisation must provide crown data for all stands to be modelled, model R7 should be used for birch and the model derived by stepwise linear regression (Table 4.24) should be used for Sitka spruce.

Fig. 5.5 Behaviour of a novel maximum crown radius model parameterised for all crown survey Sitka spruce, showing observed and modelled maximum crown radius plotted against diameter at breast height for various values of local stocking ($N_{0.01}$). For all curves, *Udbh* = 0.50.

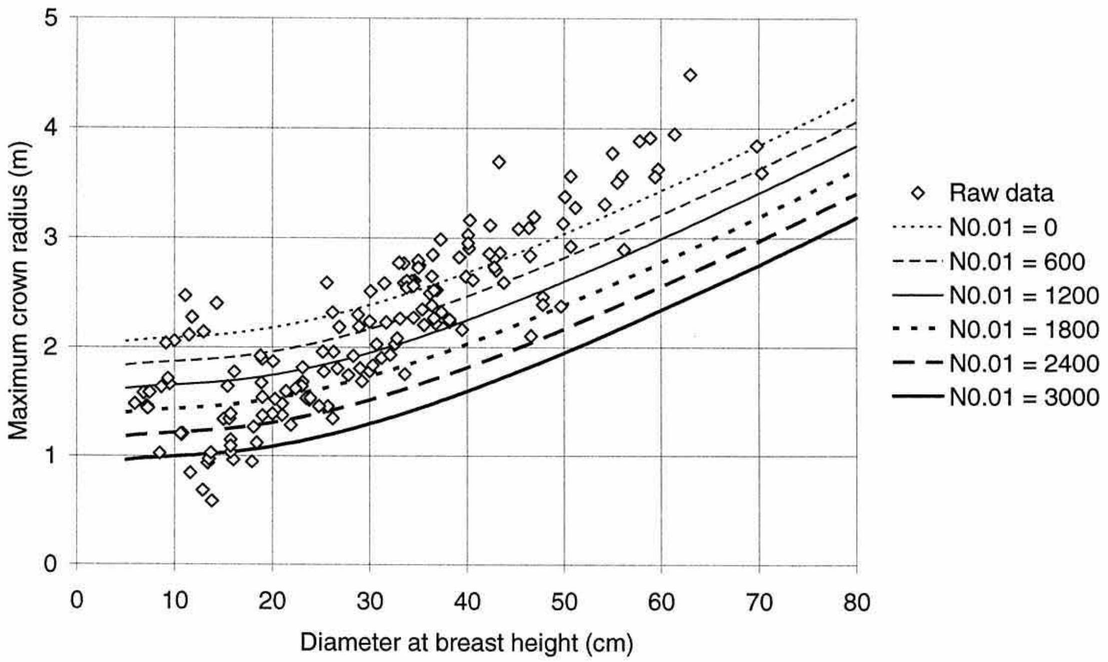
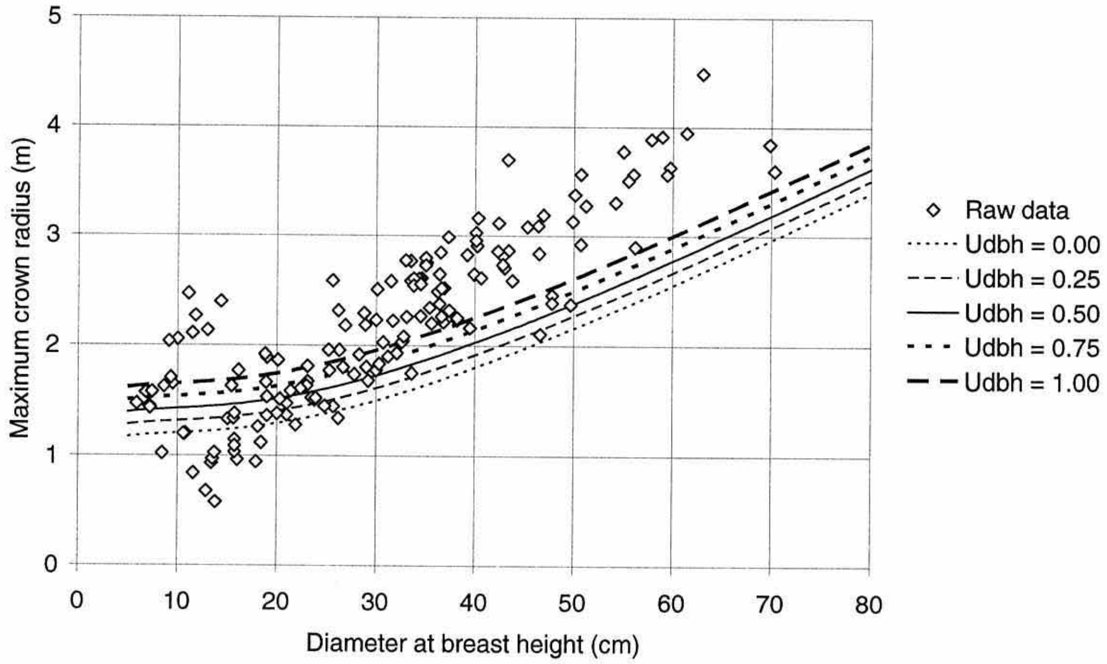


Fig. 5.6 Behaviour of a novel maximum crown radius model parameterised for all crown survey Sitka spruce, showing observed and modelled maximum crown radius plotted against diameter at breast height for various values of diameter dominance (*Udbh*). For all curves, $N_{0.01}$ = 1800.



5.3.2 Total crown length models

Of the total crown length models L1-4, L3 gave the most consistently good validation results for birch data sets (Table 4.16). Indeed, this model gave the only positive efficiency value for the CYB2 data set. Although L3 gave the highest biases for CYB1, GWY1 and the combined data set, none of these biases was significant. The behaviour of model L3 depends very much on the relationship between *dbh* and tree total height. In GWY1, where the relationship between *dbh* and height is more or less linear, crown length increases with *dbh* in such a way that height to crown base also increases steadily (Fig. 5.7). In CYB2, where height growth levels off relatively rapidly, height to crown base soon begins to decrease with *dbh* (Fig. 5.8). Since the definition of the crown base used in this study (Appendix I) does not allow *hcb* to decrease over time, this latter behaviour is obviously not realistic if the model is used to predict crown length and height to crown base for multiple time periods. Only models L1 and L2 produce consistent upwards trends in *hcb* with stem size for all birch data sets. Of these two, L2 gave slightly better validation results, but neither performed well for CYB2.

Fig. 5.7 **Behaviour of total crown length model L3 parameterised for GWY1 crown survey birch, showing modelled height to crown base and total crown length plotted against diameter at breast height.**

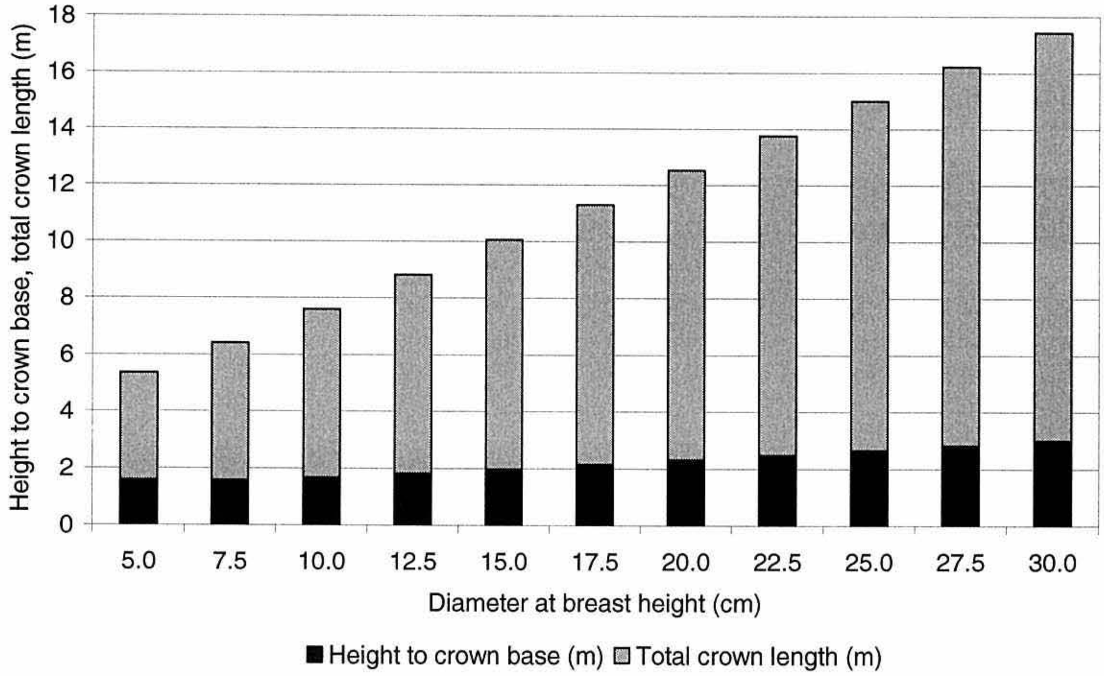
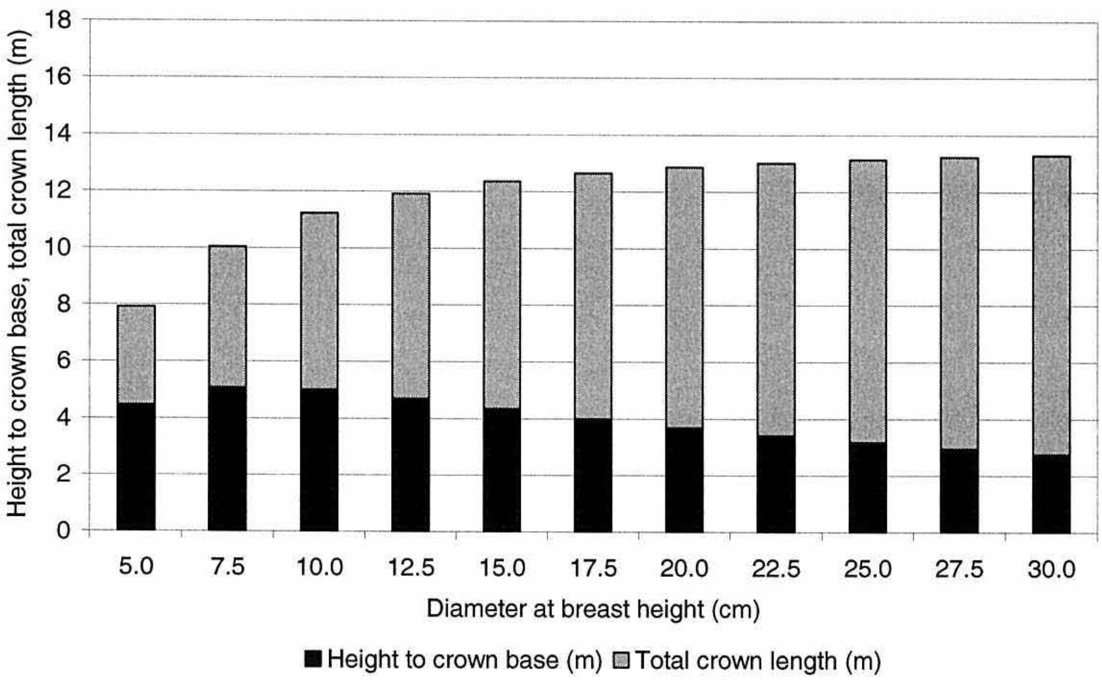


Fig. 5.8 **Behaviour of total crown length model L3 parameterised for CYB2 crown survey birch, showing modelled height to crown base and total crown length plotted against diameter at breast height.**



Novel models produced for birch using spatial variables (Table 4.25) gave some good validation results, but model forms varied greatly between data sets. Although there was little overlap between models to be applied on a site by site basis, it may be possible to apply more widely a model parameterised for the combined data set. Of the five model forms which underwent statistical validation for this data set, the model giving the best results, with an efficiency of 0.53, incorporated both height:diameter ratio and the Hegyi index:

$$(5.1) \qquad L_{total} = h \cdot e^{-(a \cdot (h/dbh) + b \cdot Hg_{0.01})}$$

where	L_{total}	= total crown length (m)
	dbh	= diameter at breast height (cm)
	h	= total height (m)
	$Hg_{0.01}$	= Hegyi competition index for 0.01 ha circular plot
	a, b	= regression coefficients

The behaviour of this model at various values of the Hegyi index is illustrated in Fig. 5.9. Crown length decreases and height to crown base increases with increasing competition (higher values of $Hg_{0.01}$). Height to crown base increases at first, but then decreases with *dbh*; the decrease is less pronounced at higher values of $Hg_{0.01}$.

Statistical validations of models L1-4 using Sitka spruce data (Table 4.16) show that model L1 gave the poorest results in all cases except GWY1 and that L3 and L4 gave the best results in most cases. The increased complexity of model L4 apparently offers very little advantage over L3. For all data sets, however, models L3 and L4 produce decreasing predictions of height to crown base at higher *dbh* values (Fig. 5.10). Model L2 does not suffer from this drawback (Fig. 5.11), and may be a better choice where predictions must be made for multiple time periods, despite its poorer validation results.

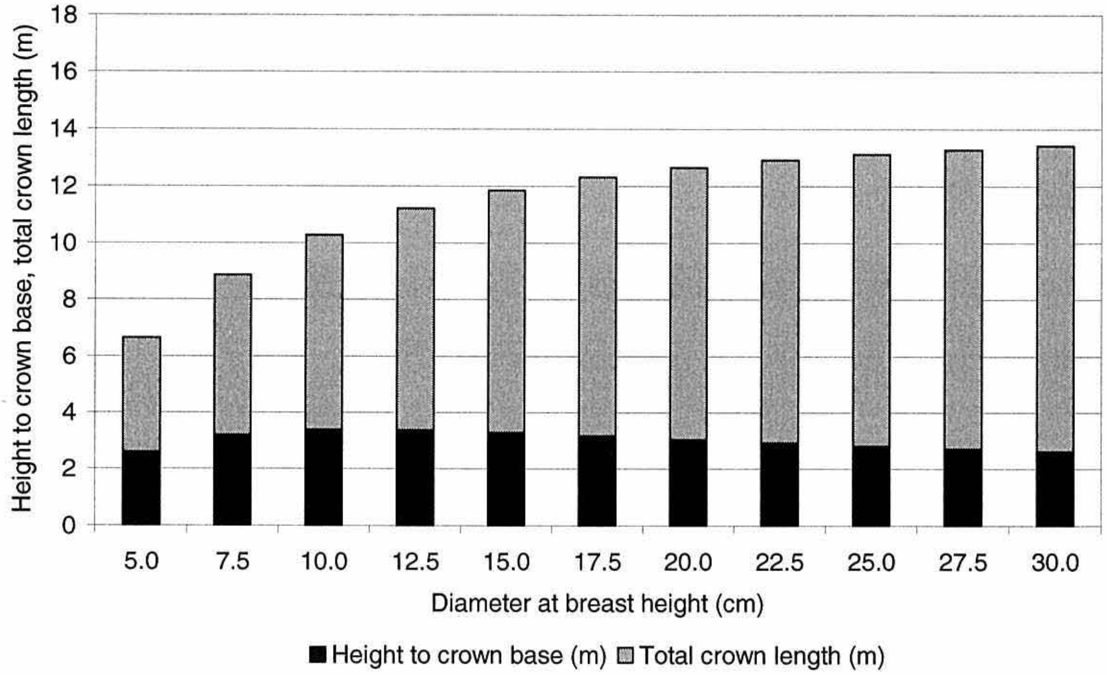
As with birch, novel models incorporating spatial variables produced good validation results (Table 4.26), but varied in form between data sets. The most widely applicable model may be that giving the best validation results for the combined data set (equation 5.2). This gave a better efficiency (0.74) than all tests of L1-4 except those for GWY1.

$$(5.2) \qquad L_{total} = h \cdot e^{-(a \cdot (h/dbh) + b/(M+1))}$$

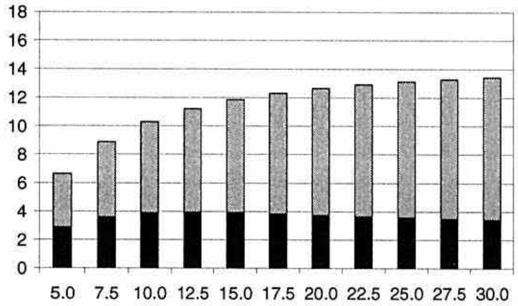
where	M	= species mingling index

Fig. 5.9 Behaviour of a novel total crown length model parameterised for all crown survey birch, showing modelled height to crown base and total crown length plotted against diameter at breast height for various values of the Hegyi index ($Hg_{0.01}$). Index values are (a) 5, (b) 10, (c) 15, (d) 20 and (e) 25.

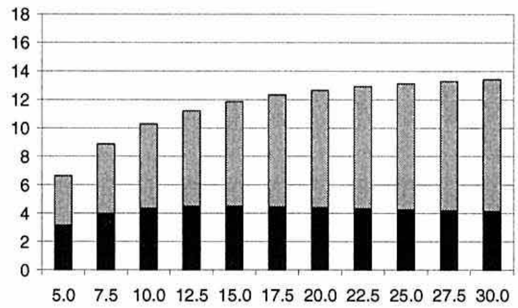
(a)



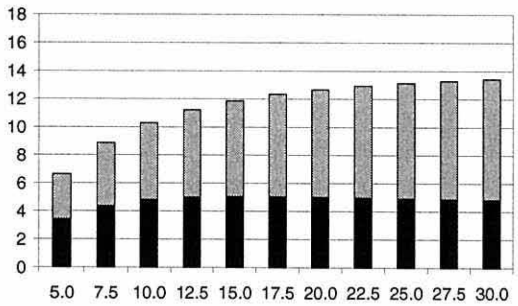
(b)



(c)



(d)



(e)

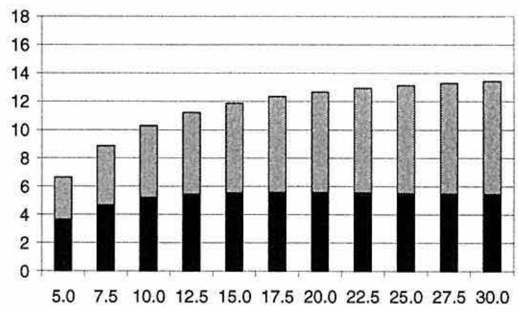


Fig. 5.10 Behaviour of total crown length model L3 parameterised for CLG2 crown survey Sitka spruce, showing modelled height to crown base and total crown length plotted against diameter at breast height.

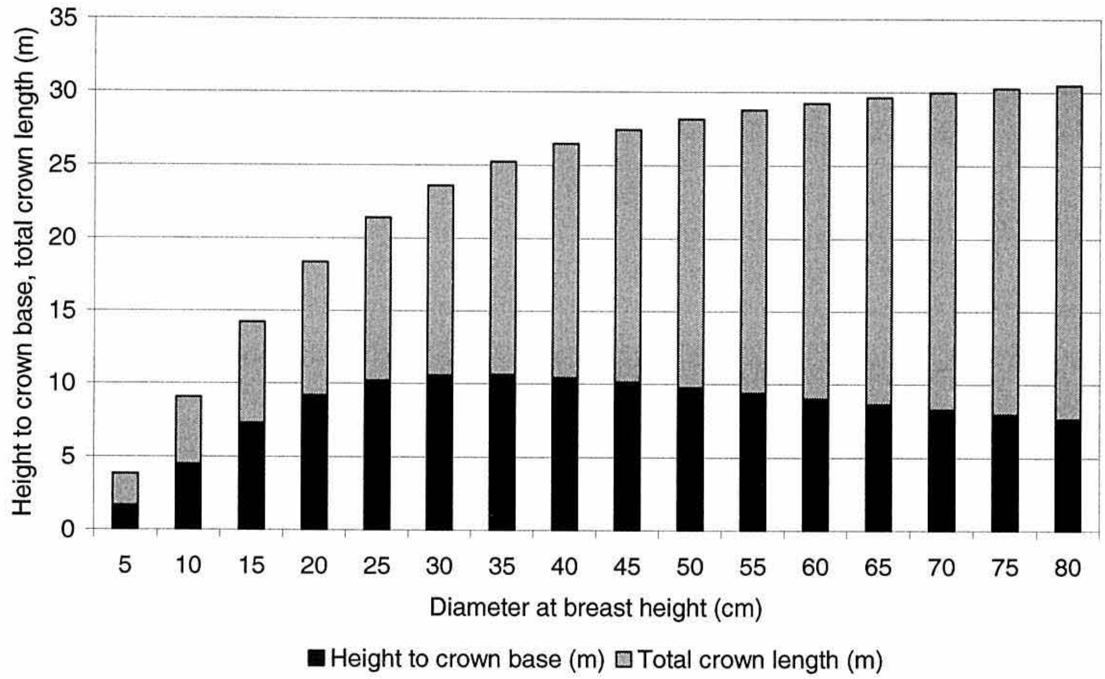
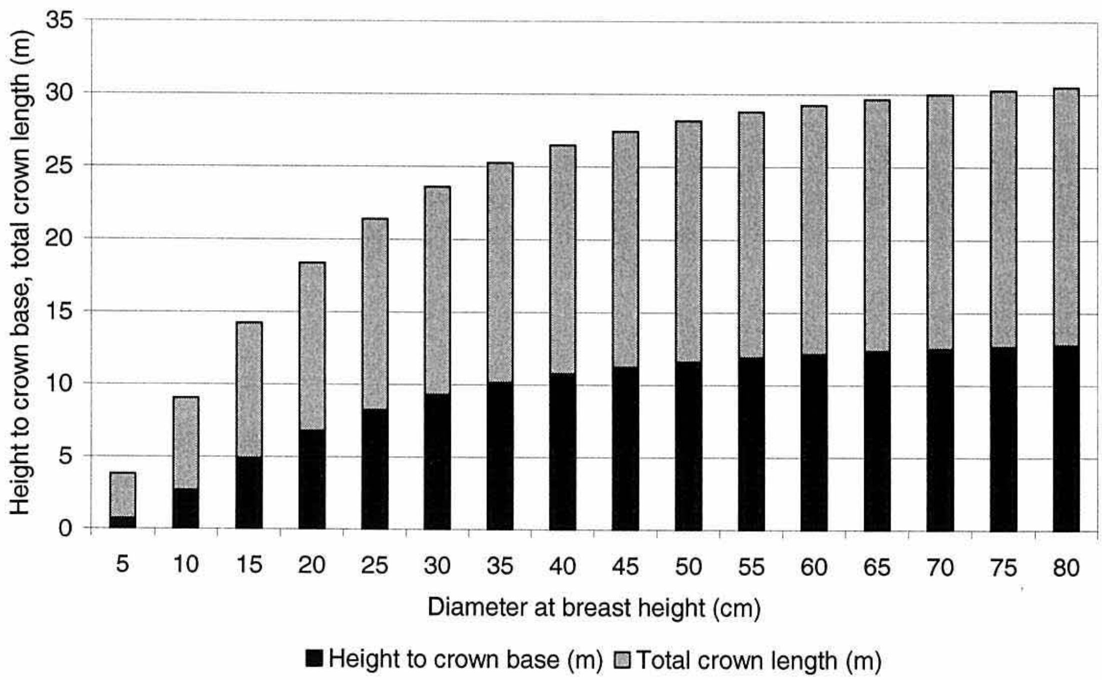


Fig. 5.11 Behaviour of total crown length model L2 parameterised for CLG2 crown survey Sitka spruce, showing modelled height to crown base and total crown length plotted against diameter at breast height.



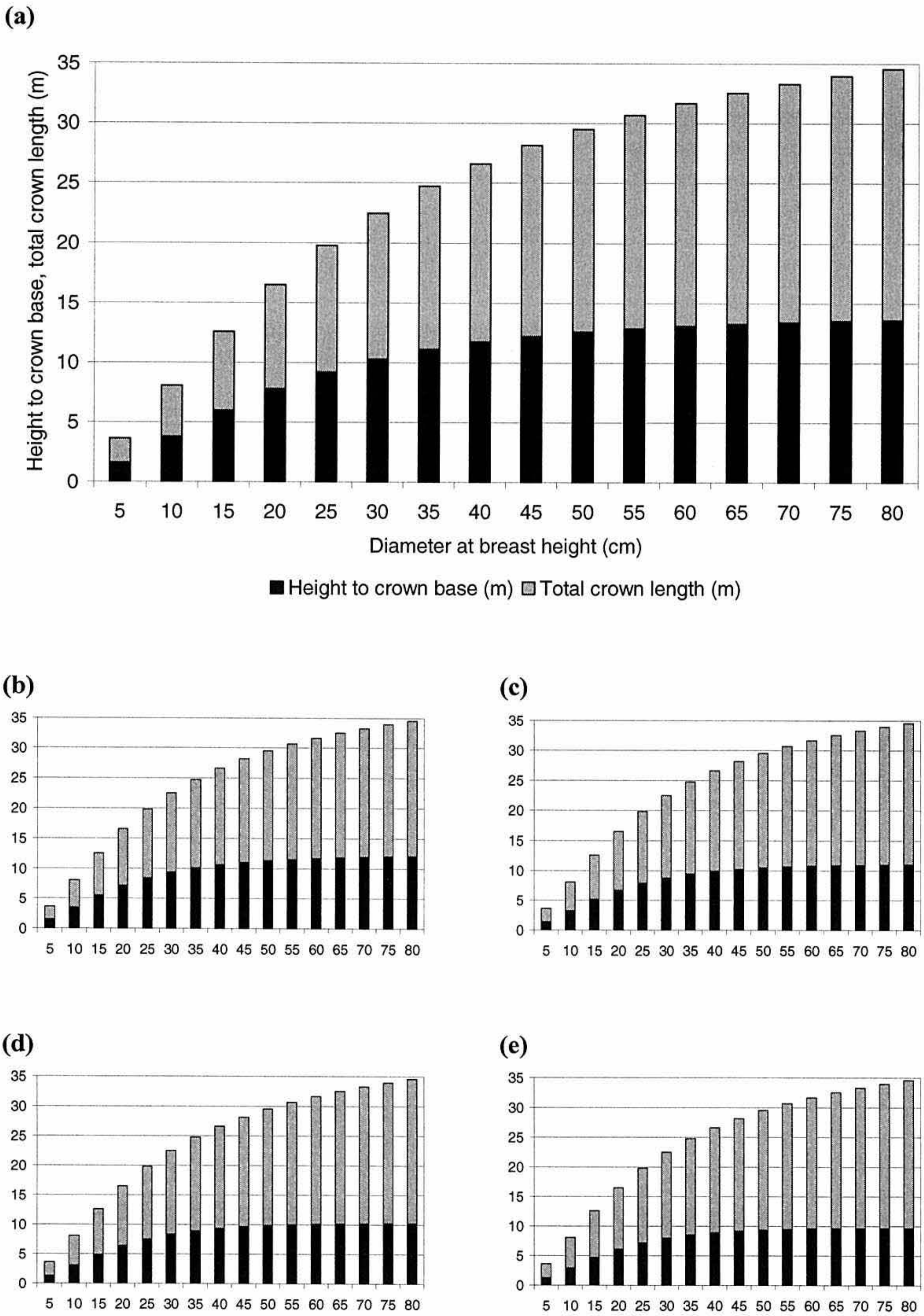
The behaviour of this model at different values of *M* is shown in Fig. 5.12. Crown length may be seen to increase as species mingling increases. In the context of the permanent sample plots, this may be because trees of species other than spruce were generally smaller or cast less dense shade. For a given value of *M*, height to crown base exhibits no downwards trend within the *dbh* range shown. However, the death or ingrowth of a single neighbouring tree could cause species mingling to increase for a reference tree, potentially causing height to crown base to decrease. This disadvantage of employing spatial variables in models can be overcome by setting *hcb* in the current time period as modelled *hcb* or as *hcb* in the previous time period, whichever is greater.

The choice of crown length models for the *Tyfiant Coed* growth model is difficult. L3 gives the best validation results for birch but can behave unrealistically; L2 is more realistic, but performs poorly for some sites. The poorer results of all models for CYB1 and CYB2 are probably due to the low quality of birch height and *hcb* data for these plots. L2 represents the best compromise between predictive power and realism for spruce when parameterised for individual sites. The model incorporating species mingling (equation 5.2) may be employed, with caution, more widely.

5.3.3 Light crown length models

Validation results for light crown length models are shown in Table 4.17. For birch, LL4 gave the best results (efficiency 0.93, bias 2.01 %), but offered only a slight improvement in efficiency over the simplest model, LL1 (efficiency 0.89, bias 11.16 %), in which light crown length is calculated as a constant proportion of total crown length. Similarly, model LL2 (efficiency 0.91, accuracy 20.18 %, bias 9.69 %) performed only slightly better for Sitka spruce in terms of accuracy than model LL1 (efficiency 0.91, accuracy 21.00 %, bias 5.69 %), and LL1 gave a lower bias. In the absence of detailed information on changes in light crown length with time in birch and spruce crowns and for the sake of model simplicity, it does not seem unreasonable to treat light crown length as roughly two thirds of birch total crown length and three quarters of Sitka spruce total crown length.

Fig. 5.12 Behaviour of a novel total crown length model parameterised for all crown survey Sitka spruce, showing modelled height to crown base and total crown length plotted against diameter at breast height for various values of the species mingling index (*M*). Index values are (a) 0.00, (b) 0.25, (c) 0.50, (d) 0.75 and (e) 1.00.



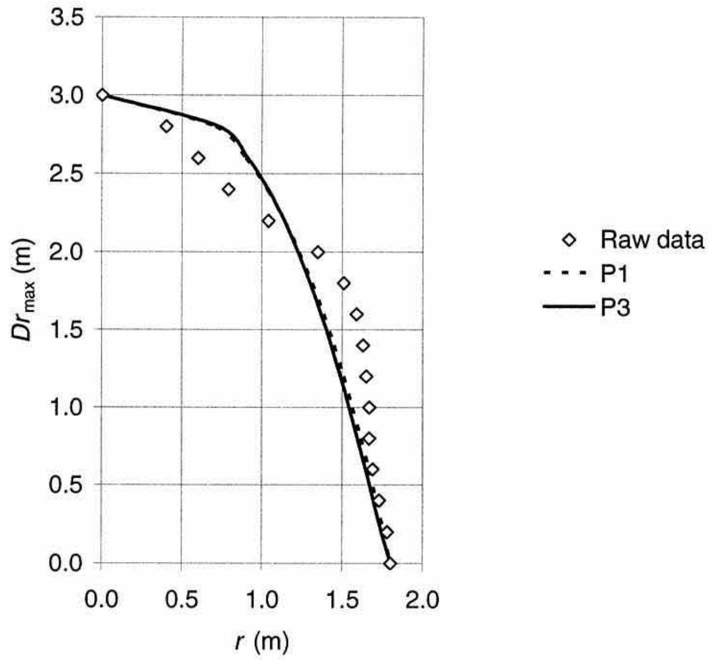
5.4 Crown profile models

The realistic behaviour of crown profile models is guaranteed by their construction, inasmuch as, for light crown profiles, crown radius is zero at the crown tip and equal to maximum crown radius at the base of the light crown, and, for shade crown profiles, crown radius is equal to maximum crown radius at the top of the shade crown and either zero (models P2 and P3) or between zero and r_{max} (P4) at the crown base. At all intermediate points, crown radius may neither exceed r_{max} nor be less than zero. This behaviour depends very much on model parameter values; it is for this reason that parameter sub-modelling must enforce appropriate parameter constraints. Some authors have observed changes in crown shape with tree age (Horn, 1971; Deleuze *et al.*, 1996; Oliver and Larson, 1996); given that crown profile data were only available for one time period in this study, this phenomenon could only be accounted for in terms of the crown shapes of trees of different sizes. Generally, therefore, given that models may be relied upon to produce realistic outputs, the choice of crown profile models for the *Tyfiant Coed* growth model may be based largely upon the results of statistical validations.

5.4.1 Birch

The validation of simultaneous parameterisations of birch light crown length models (Table 4.31) yielded higher efficiency values for models P1 (mean 0.85) and P3 (mean 0.86) than for P2 (mean 0.72). All three models produced significantly biased results in at least 80 % of cases. For this parameterisation method, there is no obvious basis on which to choose between models P1 and P3. Example profiles generated using these two models are shown in Fig. 5.13 and differ very little.

Fig. 5.13 GWY1 birch tree 256 light crown profiles for models P1 and P3 with simultaneous parameterisation, showing observed and modelled crown radius (*r*) plotted against distance from the point of maximum crown radius (Dr_{max}).



Parameter sub-modelling for birch light crown profile models gave broadly similar results (Table 4.32); model P2 gave the poorest efficiency results (mean 0.75), results were generally good for P1 (mean 0.87) and P3 (mean 0.83), and all models produced significantly biased results in most cases. Model P1 performed slightly better overall, combining consistently high efficiencies with relatively low biases. Parameter sub-models for these three models incorporated the variables maximum crown radius, total crown length and light crown length, suggesting that the shape of the light crown is determined solely by crown size rather than by competitive interactions with other crowns. This is in agreement with the observation by Honer (1971) and Cluzeau *et al.* (1994) that the portions of crowns growing free from competition are the same shape as the crowns of open-grown trees.

Neither simultaneous parameterisation nor parameter sub-modelling seems to offer any obvious advantage for the parameterisation of birch light crown profile models, as both methods produced similar model efficiencies and biases. High levels of bias may be due to the small sizes of the parameterisation and validation data set sizes, although similar levels of bias occurred with the larger spruce data sets (see section 5.4.2), or it may be that the models tested are simply not suitable for birch crown shapes. Overall, model P1 with parameter sub-modelling may be the best choice for birch light crown profiles, with its high average efficiency (0.87) and lower rate of significant biases (60 %).

Birch shade crown profile modelling results for both simultaneous parameterisation and parameter sub-modelling were very poor (Tables 4.31 and 4.32 respectively), with many negative efficiency values. Efficiencies were mostly compromised by the failure of models to account for variation in the width of the crown base. Fig. 5.14(a) shows the outputs of simultaneous parameterisations of models P2-4 for GWY1 tree 815. All three models gave negative efficiencies in this case, where the crown base is relatively wide ($r = 0.95$ m). Fig. 5.14(b) shows outputs for tree 256, where crown base $r = 0.03$ m and models gave efficiencies from 0.73 to 0.95. A hybrid of models P3 and P4 might resolve this problem, combining the ability of P4 to set crown base radius between zero and $r_{\max}$ with the ability of P3 to describe the curve of the shade crown profile:

(5.3) $$r = a \cdot r_{\max} + (1-a) \cdot r_{\max} \cdot \left(1 - \left(Dr_{\max} / L_{shade}\right)^{b}\right)^{c} \qquad 0 \le a \le 1,\ 0 < b, c$$

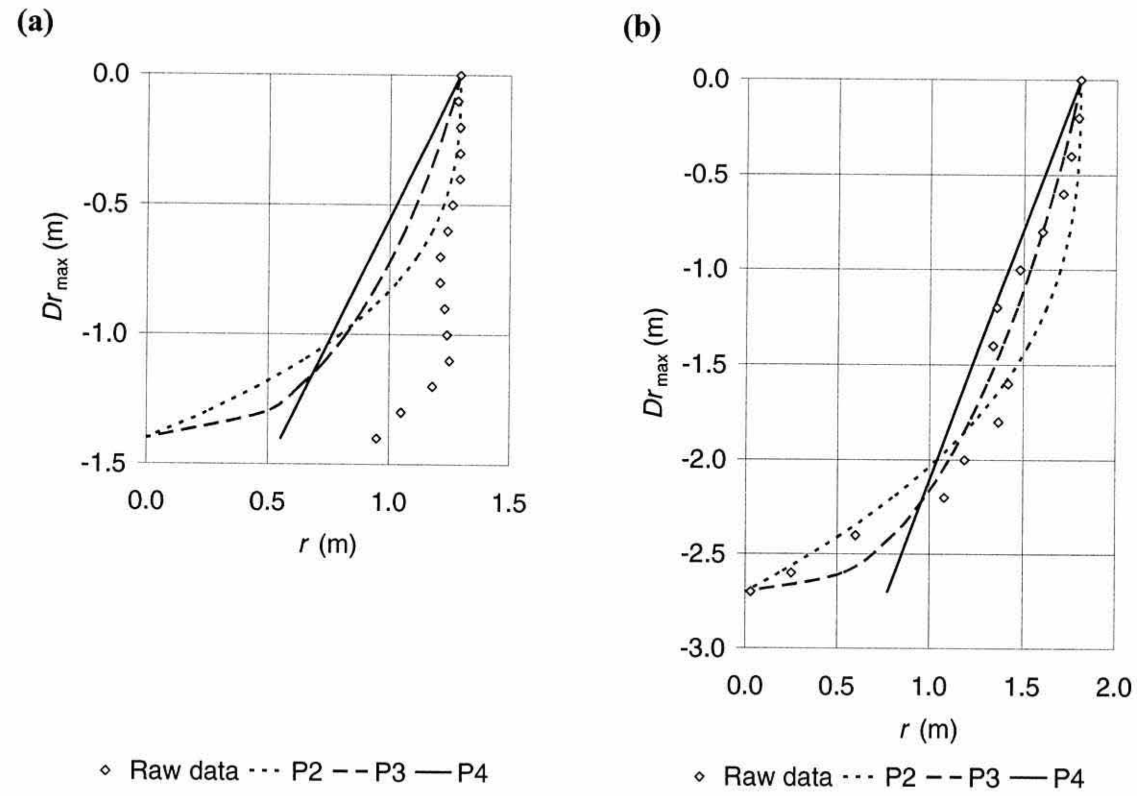
where

	r	= crown radius (m)
	$Dr_{\max}$	= vertical distance from height of maximum crown radius (m)
	L_{shade}	= shade crown length (m)
	$r_{\max}$	= maximum crown radius (m)
	a, b, c	= regression coefficients

Here the coefficient a determines the width of the crown base as a proportion of maximum crown radius.

On the basis of the results currently available for birch, model P4 with simultaneous parameterisation gave the highest proportion of positive efficiencies (60 %) and so seems to be the most widely applicable model, at least.

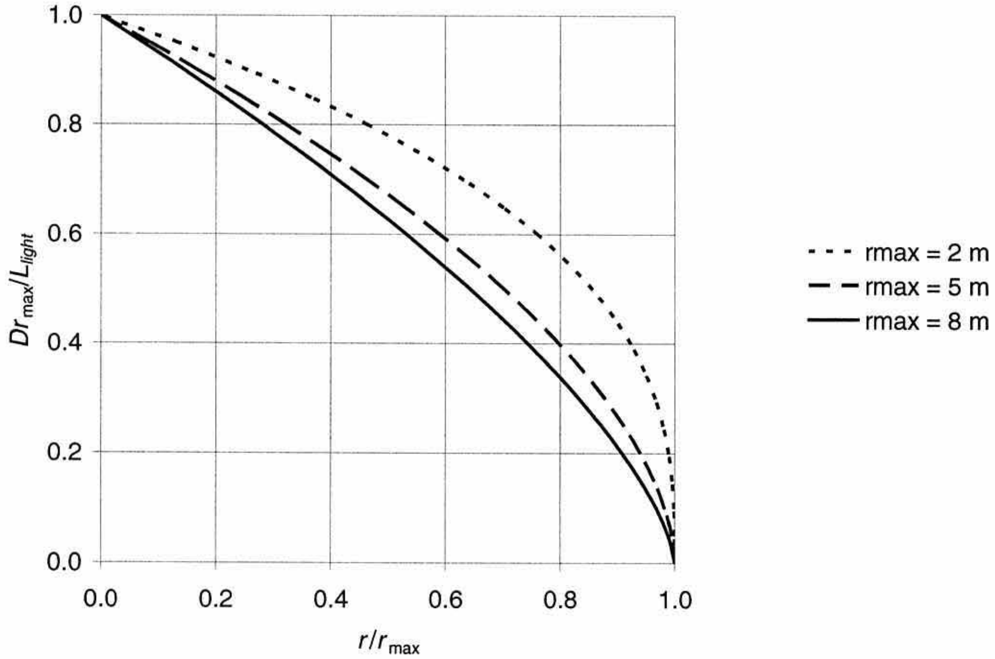
Fig. 5.14 Birch shade crown profiles for models P2-4 with simultaneous parameterisation, showing observed and modelled crown radius (*r*) plotted against distance from the point of maximum crown radius (Dr_{max}) for GWY1 trees (a) 815 and (b) 256.



5.4.2 *Spruce*

Of the light crown profile models, both with simultaneous parameterisation and parameter sub-modelling, P1 consistently gave the worst statistical validation results for Sitka spruce (Tables 4.33 and 4.34). There was relatively little difference in the performances of models P2 and P3 with simultaneous parameterisation, with both models giving mean efficiencies of 0.95. P3 produced slightly fewer significant biases, but biases were still significant in the majority of cases. There was greater differentiation between models P2 and P3 with parameter sub-modelling. P2 gave the highest efficiency value in nine of 14 cases, with a mean of 0.96. P3 gave the highest efficiency in only four of 14 cases, with a mean of 0.94. Both models produced biased results in most cases. Interestingly, as with birch light crown profile models, the parameter sub-model for the more successful model P2 was based on crown dimensions alone (light crown length and maximum crown radius, equation 4.10); the sub-models for P3, conversely, were based on indicators of competition (basal area of neighbouring trees and height:diameter ratio, equations 4.11 and 4.12). Differences in crown shapes generated using model P2 with different ratios of light crown length to maximum crown radius, covering approximately the range of ratios in the GWY1 spruce data set, are illustrated in Fig. 5.15. There is a shift towards a more convex and less conic crown shape as maximum crown radius decreases and L_{light}/r_{max} increases. If older trees are assumed to have proportionally narrower crowns, this pattern is in accordance with the observation by Deleuze *et al.* (1996) that "the conical form of young [conifer] trees becomes more rounded when the trees become mature".

Fig. 5.15 GWY1 Sitka spruce light crown profiles for model P2 with parameter sub-modelling for various values of L_{light}/r_{max}. For all curves, L_{light} = 10 m. Vertical and horizontal crown dimensions are shown as proportions of light crown length and maximum crown radius respectively.



The high incidence of significant biases even in this larger spruce data set is a cause for concern, suggesting a problem either with model construction, parameterisation or validation. There is no obvious predominance of positive or negative biases, suggesting that biases are not the result of a systematic difference between parameterisation and validation data sets, although average light crown length was higher in the parameterisation data set (9.6 m) than in the validation set (6.1 m). It may be the case that even parameter sub-modelling is not sufficiently sophisticated to account for variation in crown shape between trees. Of the modelling approaches tested in this study, model P2 with parameter sub-modelling offered the most consistently good validation results, biases notwithstanding.

With both simultaneous parameterisation and parameter sub-modelling, models P2 and P3 produced negative efficiencies in most cases (for between 64 % and 79 % of trees) when applied to spruce shade crowns (Tables 4.33 and 4.34). Model P4 gave far fewer negative efficiencies (for 7 to 14 % of trees). The better performance of P4 is no doubt due to the fact that the spruce sample trees had relatively wide crown bases, with radii ranging from 0.18 to 3.57 m (mean 1.22 m), or from 11 to 84 % (mean 47 %) of maximum crown radius. Parameter sub-modelling gave the fewest negative efficiencies for P4, with a mean of 0.48, although it gave slightly more significant biases (in 43 % of cases, compared with 29 % for simultaneous parameterisation). The parameter sub-model for P4 was based on the basal area of trees in a 0.02 ha plot (equation 4.16), suggesting that the shape of the shade crown is determined largely by interaction with neighbouring trees. Given the range of $BA_{0.02}$ values present in the GWY1 spruce sample (13.2-44.1 m^2 ha^{-1}), the P4 parameter a could assume values from 0.46 to 0.78, resulting in crown base radii from 46 to 78 % of maximum crown radius.

For spruce shade crown profile modelling with reasonably consistent standards, P4 with parameter sub-modelling seems to be the best choice. The hybrid model suggested for birch shade crowns (equation 5.3) might improve validation results further.

5.5 Crown profile assessment methods

Issues relating to fieldwork and analyses for the crown window and terrestrial photogrammetry are discussed in sections 5.1.2 and 5.1.3. This section concentrates on the outputs of the two methods and potential future applications of photogrammetric techniques, exemplified by crown reconstruction.

5.5.1 *Comparison of methods*

The comparison of crown profile assessment methods was carried out for a number of reasons. First and foremost it was intended to determine whether the crown window and terrestrial photogrammetry could produce comparable crown dimension and profile data. To a limited degree, it allowed data from these two methods to be proofed by comparison with direct measurements of crown dimensions. Also, the comparison was used to establish whether one method offered advantages over the other in terms of fieldwork, analysis and output data.

Work on birch was limited by problems encountered during photogrammetric analysis (see section 4.3.1). Ultimately it was only possible to derive maximum crown radius values from direct measurements and the crown window. Direct measurements were found to be consistently and significantly greater (section 4.3.2, Table 4.10). This is contrary to expectations (see section 3.2.5), and is difficult to explain unless an error occurred in the scaling of crown window profiles; for example, a different point in a crown outline may have been identified as the crown base to that used in the field to measure crown length.

Successful photogrammetry for spruce meant that a full range of data comparisons was possible. The crown window and photogrammetry were found to produce very similar estimates of light crown length, shade crown length and maximum crown radius, with no significant differences (section 4.3.2, Table 4.11). The use of ranging rods to scale 3-D models in photogrammetric analyses proved to be justified, as total crown lengths derived from models were very similar to direct measurements. Both crown window and photogrammetry maximum crown radii were significantly greater than direct measurements, as crown window and photogrammetry estimates were based, directly or indirectly, on the horizontal extent of branches whereas direct measurements typically fell between branch tips (see section 3.2.5). These results showed that the two methods of crown profile assessment produced comparable crown dimension data and that these data were related to direct measurements in a logical fashion.

Comparisons of radii throughout crown profiles showed that mean differences between crown window and photogrammetry profiles were relatively small (see section 4.3.3).

However, despite the fact that the largest absolute difference in radius was only 0.11 m, differences were found to be significant for two of the three sample trees. For tree 1, photogrammetry tended to produce lower estimates of crown radius, while, for tree 2, the crown window produced lower estimates. In the former case, photogrammetry may under-estimate crown radius because of the influence of unusually short branches on the mean branch tip per whorl, as may be observed in the seventh whorl of spruce sample tree 1 (Fig. 4.12(a)) which includes a branch tip at r = 0.90 m, D_{tip} = -3.06 m. In the latter case, the crown window may underestimate radius if the longer branches in each whorl do not fall perpendicular to either drawn crown outline and therefore have a relatively small impact on mean radius. The main difference between the two methods is that in photogrammetric analysis all branches, long or short, affect the crown profile, whereas the crown window generally gives no weight to unusually short branches and may, by chance, give relatively little weight to exceptionally long branches. These differences in crown profiles did not, however, lead to significant differences in crown profile model parameters (Table 4.12). Parameterisations using crown profile data produced slightly higher R^2 values in six of nine cases, but the largest difference was only 0.03 (mean absolute difference 0.006). On the basis of these results, data from both sources seem to be equally well suited to Sitka spruce light crown profile modelling. Shade crown profile modelling might prove more problematic with photogrammetry data as, depending on branching angles, the lowest mean branch tip may be above or below the crown base. Where the mean branch tip was above the crown base, crown base radius could be set as zero. Where the mean branch tip was below the crown base, crown base radius could be taken as the radius of the lowest branch tip or could be interpolated between the lowest and second lowest branch tips.

For both crown profile assessment methods, fieldwork can be carried out relatively quickly, weather conditions permitting, and it is the computer analysis that is time-consuming. Analysis times are shorter for crown window data, and this method has the further advantage that it can be used to gather crown shape data for a greater range of tree sizes and species than appears to be the case for photogrammetry. The greatest advantage of terrestrial photogrammetry, however, is that crown photographs can potentially yield far more information than outlines drawn using the crown window.

5.5.2 *Opportunities presented by photogrammetry*

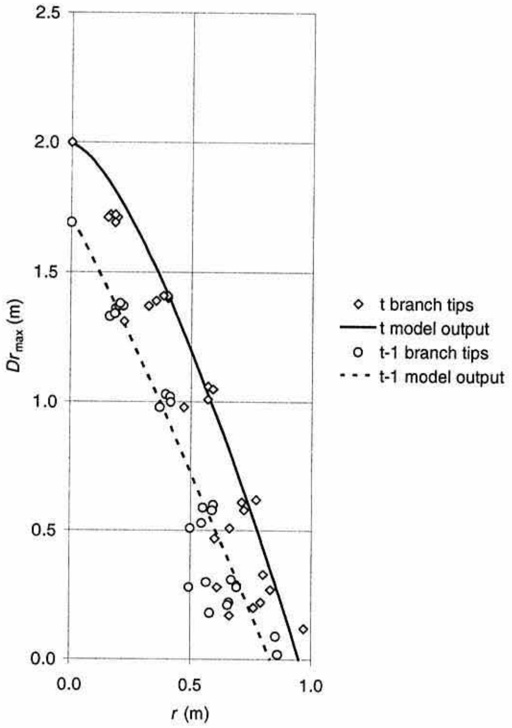
In the context of crown modelling, one way in which terrestrial photogrammetry can yield more data is through the reconstruction of previous growing seasons' crown extents (see sections 3.2.4 and 4.3.4). Crown reconstruction can produce crown dimension and profile data for multiple time periods from a single set of photographs, potentially facilitating limited dynamic modelling using results from a single fieldwork season. There are limitations to this approach; it is unlikely to be feasible for large trees, it is only possible for species whose branching structure readily permits previous years' branch tips to be identified, and it cannot account for changes in branching angles, so reconstructed crown profile data must be treated with some caution. Work in CYB3, however, has shown that reconstruction is possible for Sitka spruce up to 4 m in height.

Crown profile models were successfully applied to branch tip data from two time periods, t and t-1 (see section 4.3.4). A single growing season apparently had relatively little effect on crown shape, as model parameter values showed no significant differences between time periods. Model parameter values for the smallest tree (3 m in height) showed the greatest differences, however, and resulted in changes from approximately conic crown shapes to more convex shapes for all three light crown profile models (Fig. 5.16). As with model P2 parameter sub-modelling for spruce (see section 5.4.2), this trend in crown shape matches the observations of Deleuze *et al.* (1996) regarding excurrent conifers. Note that, for crown profile modelling, reconstructed crown data were translated so that the t-1 crown tip was the origin of the co-ordinate system (cf. Fig. 4.13, where the t crown tip was used as the co-ordinate system origin for both time periods).

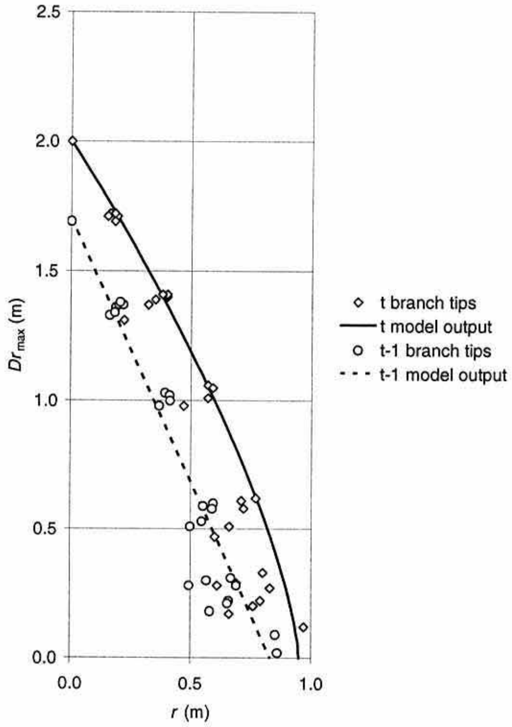
Stronger relationships were observed between whorl base D_{tip} and whorl mean relative increment for each sample tree than between whorl base D_{tip} and whorl mean absolute increment (see section 4.3.4). The former, stronger relationship suggests that there is scope for dynamic crown profile modelling in terms of height increment and branch extension based on photogrammetry data. In order to produce accurate crown profiles, however, it would be necessary to find a method for modelling past branching angles.

Fig. 5.16 Light crown profile models fitted to current and reconstructed data for CYB3 Sitka spruce sample tree 2, showing observed and modelled crown radius (*r*) plotted against distance from the point of maximum crown radius (Dr_{max}) for time periods *t* and *t*-1 for models (a) P1, (b) P2 and (c) P3.

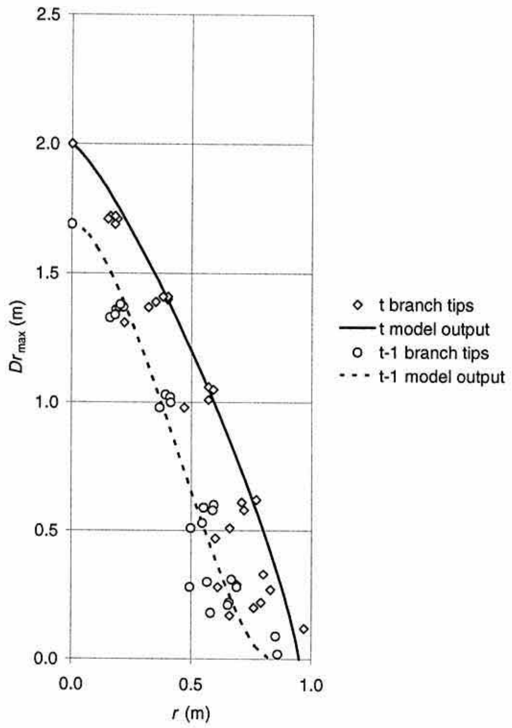
(a)



(b)

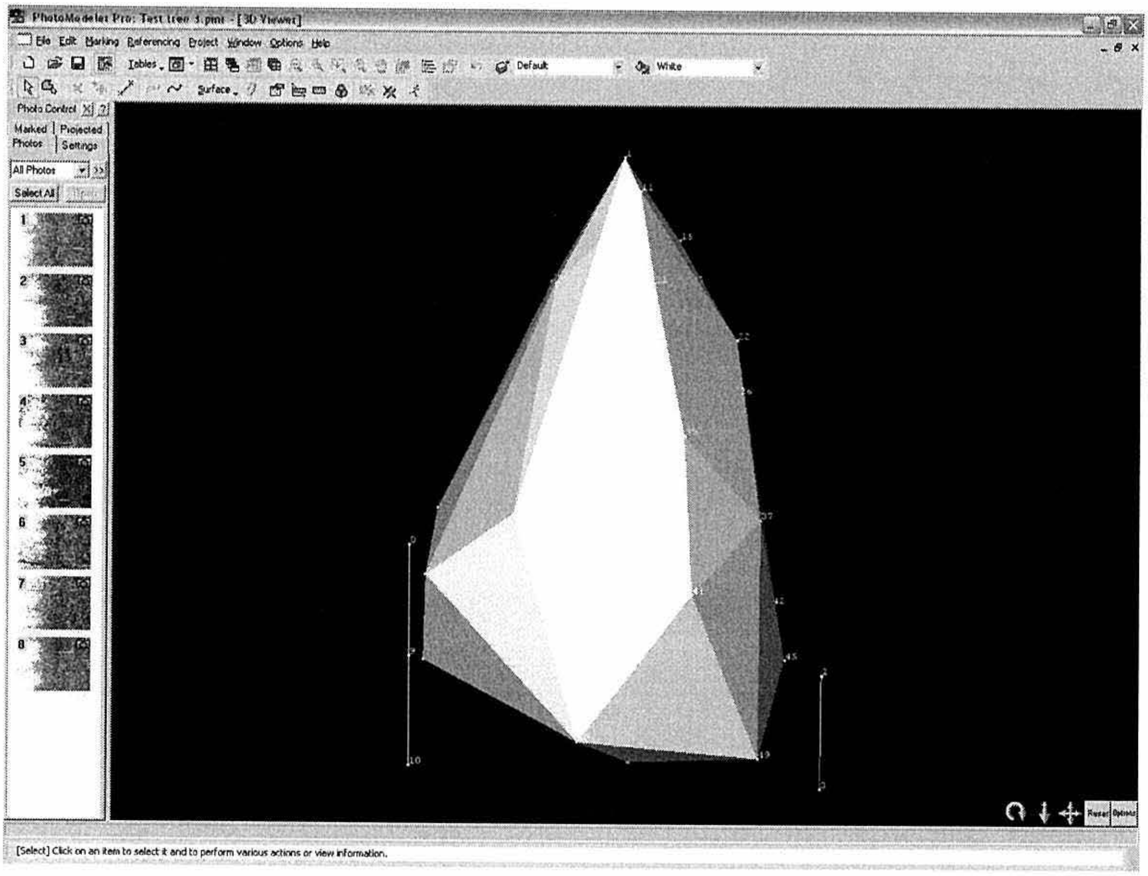


(c)



For species with branches in discrete whorls, the reconstruction of height increment is an obvious potential by-product of crown reconstruction which may be of value to the modeller in its own right. The investment of more time and effort in photogrammetric analysis can yield considerable quantities of information on branching structure (Riedel, 2002). Data on branch segment lengths and diameters could feed into estimates of biomass, or data on segment length and angles between segments could form the basis for extremely detailed crown models. A feature of PhotoModeler with great potential is the ability of the software to create a 3-D convex hull to enclose branch tip points (Fig. 5.17), allowing rapid calculation of crown surface area and volume.

Fig. 5.17 Crown surface area screenshot, showing the 3-D convex hull generated in PhotoModeler to enclose CYB3 sample tree 3 branch tips.



The usefulness of terrestrial photogrammetry techniques is not limited to crown modelling. Photogrammetry can be used to assess stem volume and taper (Gaffrey *et al.*, 2001; Dean, 2003), and PhotoModeler has even been used to measure the extent of bark stripping by grey squirrels (*Sciurus carolinensis* Gmelin) (Groiser, 2006).

5.6 Potential areas for further research

As section 5.5.2 indicates, there is considerable scope to explore further the contribution to crown modelling of terrestrial photogrammetry. In particular, it is necessary to determine the limits of photogrammetric methods in terms of the size and species of subject trees for which they are suitable and the conditions, in terms of season, weather and stand structure, under which photography of sufficiently high quality is feasible. Crown reconstruction, which potentially facilitates dynamic crown modelling, requires testing to establish the effects of changes in branching angles. The most obvious approach would be to undertake photogrammetric analyses of sample trees in two consecutive years, comparing crown data from the first year with reconstructed crown data generated from the second year's photographs. It may prove possible to account for changes in angles with a mathematical function; Cochrane and Ford (1978) observed that Sitka spruce branches were formed at the same angle, but that angles subsequently decreased with depth in the canopy. If crown reconstruction is shown to produce data of acceptable accuracy, robust and realistic dynamic models of crown dimensions and shape may be within reach.

Dynamic modelling will also become a possibility following the remeasurement of the *Tyfiant Coed* permanent sample plots. It may prove possible to predict changes in maximum crown radius from changes in the size or configuration of a tree's neighbours. Crown length models could be replaced with more realistic crown base recession models. Repeat assessments of crown shape would allow the quantification of general statements regarding changes in crown shape with age (e.g. Oliver and Larson, 1996, p. 60). If, however, dynamic modelling was not considered necessary or was found to be unfeasible, plot remeasurements would also offer scope for the improvement of static models, primarily through the availability of larger crown measurement data sets. In addition, model forms and spatial variables not used in this study could be considered; one area where refinement is possible is the selection of competitors, for which many methods exist (e.g. Biging and Dobbertin, 1992).

Far more complex, 3-D crown modelling approaches (e.g. Cescatti, 1997) could be pursued. While these approaches may, in most cases, represent an unnecessary level of complication for the quantification of competition within the *Tyfiant Coed* model, they might overcome problems encountered during the modelling of suppressed birch crowns (see section 5.2), and might therefore elucidate the effects of extremes of competition on growth. Three-dimensional data could come from direct measurements, the crown window or photogrammetry.

The data currently available from this study allow crown dimension and profile models to be ranked according to validation performance and behaviour. Ultimately, however, absolute levels of performance must be judged according to the contributions made by these models to the quantification of competition, growth and yield within the *Tyfiant Coed* model. This is a long-term process, and depends upon the maintenance and remeasurement of the permanent sample plots and a sustained commitment to growth modelling.

REFERENCES

Aguirre, O., Hui, G., Gadow, K. von and Jiménez, J. (2003). An analysis of spatial forest structure using neighbourhood-based variables. *Forest Ecology and Management*, **183**, 137-145.

Amberger, H., Marx, U. and Staap, A.F. (1990). Ein neues Gerät zur Vermessung von Baumkronen. (A new instrument for measurement of tree crowns.) *Allgemeine Forstzeitschrift*, **27**, 709-711.

Assmann, E. (1970). *The Principles of Forest Yield Study*. Oxford: Pergamon Press.

Ayhan, H.O. (1977). A crown radius instrument. *Scottish Forestry*, **31**, 67-70.

Bai, Y., Walsworth, N., Roddan, B., Hill, D.A., Broersma, K. and Thompson, D. (2005). Quantifying tree cover in the forest-grassland ecotone of British Columbia using crown delineation and pattern detection. *Forest Ecology and Management*, **212**, 92-100.

Beekhuis, J. (1965). Crown depth of radiata pine in relation to stand density and height. *New Zealand Journal of Forestry*, **10**, 43-61.

Berezovskava, F.S., Karev, G.P., Kisliuk, O.S., Khlebopros, R.G. and Tsel'niker, Y.L. (1997). A fractal approach to computer-analytical modelling of tree crowns. *Trees: Structure and Function*, **11**, 323-327.

Biging, G.S. and Dobbertin, M.S. (1992). A comparison of distance-dependent competition measures for height and basal area growth of individual conifer trees. *Forest Science*, **38**, 695-720.

Biging, G.S. and Gill, S.J. (1997). Stochastic models for conifer tree crown profiles. *Forest Science*, **43**, 25-34.

Biging, G.S. and Wensel, L.C. (1990). Estimation of crown form for six conifer species of northern California. *Canadian Journal of Forest Research*, **20**, 1137-1142.

Bonnor, G.M. (1964). The influence of stand density on the correlation of stem diameter with crown width and height for lodgepole pine. *Forestry Chronicle*, **40**, 347-349.

Bonnor, G.M. (1968). Stem diameter estimates from crown width and tree height. *Commonwealth Forestry Review*, **47**, 8-13.

Brewer, L.C., Byrd, D.O., Rea, P.W. and Roberts, E.G. (1959). A device for measuring crown diameters of open grown trees. *Journal of Forestry*, **57**, 577.

Briggs, D. (1996). Modeling crown development and wood quality. *Journal of Forestry*, **94**, 24-25.

Buell, J.H. (1936). Crown mapping simplified by the use of an Abney level and a mirror. *Journal of Forestry*, **34**, 77-78.

Canham, C.D., Coates, K.D., Bartemucci, P. and Quaglia, S. (1999). Measurement and modeling of spatially-explicit variation in light transmission through interior cedar-hemlock forests of British Columbia. *Canadian Journal of Forest Research*, **29**, 1775-1783.

Cannell, M.G.R. (1974). Production of branches and foliage by young trees of *Pinus contorta* and *Picea sitchensis*: Provenance differences and their simulation. *Journal of Applied Ecology*, **11**, 1091-1115.

Cescatti, A. (1997). Modelling the radiative transfer in discontinuous canopies of asymmetric crowns. I. Model structure and algorithms. *Ecological Modelling*, **101**, 263-274.

Cluzeau, C., Dupouey, J.L. and Courbaud, B. (1995). Polyhedral representation of crown shape. A geometric tool for growth modelling. *Annales des Sciences Forestières*, **52**, 297-306.

Cluzeau, C., Goff, N. le and Ottorini, J.-M. (1994). Development of primary branches and crown profile of *Fraxinus excelsior*. *Canadian Journal of Forest Research*, **24**, 2315-2323.

Cochrane, L.A. and Ford, E.D. (1978). Crown of a Sitka spruce plantation: analysis and stochastic description of the developments of the branching structure. *Journal of Applied Ecology*, **15**, 227-244.

Cole, W.G. and Lorimer, C.G. (1994). Predicting tree growth from crown variables in managed northern hardwood stands. *Forest Ecology and Management*, **67**, 159-175.

Colin, F. and Houllier, F. (1992). Branchiness of Norway spruce in northeastern France: predicting the main crown characteristics from usual tree measurements. *Annales des Sciences Forestières*, **49**, 511-538.

Coyea, M.R. and Margolis, H.A. (1992). Factors affecting the relationship between sapwood area and leaf area of balsam fir. *Canadian Journal of Forest Research*, **22**, 1684-1693.

Cucchi, V., Meredieu, C., Stokes, A., Coligny, F. de, Suarez, J. and Gardiner, B.A. (2005). Modelling the windthrow risk for simulated forest stands of maritime pine (*Pinus pinaster* Ait.). *Forest Ecology and Management*, **213**, 184-196.

Curtis, R.O. and Reukema, D.L. (1970). Crown development and site estimates in a Douglas-fir plantation spacing test. *Forest Science*, **16**, 287-301.

Davies, O. (2001). *Relating annual radial increment to cone and seed production in native Scots pine (*Pinus sylvestris *L. ssp.* scotica *(Schott) Warb.) woodlands in Deeside*. BSc thesis, School of Agricultural and Forest Sciences, University of Wales, Bangor.

Dean, C. (2003). Calculation of wood volume and stem taper using terrestrial single-image close-range photogrammetry and contemporary software tools. *Silva Fennica*, **37**, 359-380.

Deleuze, C., Hervé, J.C., Colin, F. and Ribeyrolles, L. (1996). Modelling crown shape of *Picea abies*: spacing effects. *Canadian Journal of Forest Research*, **26**, 1957-1966.

Dyer, M.E. and Burkhart, H.E. (1987). Compatible crown ratio and crown height models. *Canadian Journal of Forest Research*, **17**, 572-574.

Edwards, P.N. and Christie, J.M. (1981). Yield Models for Forest Management. *Forestry Commission Booklet 48*. Edinburgh: Forestry Commission.

Eos Systems Inc. (2003). *PhotoModeler Pro 5 User Manual*. Vancouver: Eos Systems Inc.

Evans, D.L., Roberts, S.D. and Parker, R.C. (2006). LiDAR – A new tool for forest measurements? *Forestry Chronicle*, **82**, 211-218.

Fahlvik, N., Ekö, P.-M. and Pettersson, N. (2005). Influence of precommercial thinning grade on branch diameter and crown ratio in *Pinus sylvestris* in southern Sweden. *Scandinavian Journal of Forest Research*, **20**, 243-251.

Farr, W.A., DeMars, D.J. and Dealy, J.E. (1989). Height and crown width related to diameter for open-grown western hemlock and Sitka spruce. *Canadian Journal of Forest Research*, **19**, 1203-1207.

Forestry Commission (1921). *First Annual Report of the Forestry Commissioners*. Year ending September 30th, 1920. London: HMSO.

Forestry Commission (2001). *Coetiroedd i Gymru: Y Cynulliad Cenedlaethol i Gymru Strategaeth am Coed a Choetir/Woodlands for Wales: The National Assembly for Wales Strategy for Trees and Woodlands*. Edinburgh: Forestry Commission.

Forestry Commission (2004a). *Forestry Statistics 2004*. Edinburgh: Forestry Commission.

Forestry Commission (2004b). *The UK Forestry Standard*. Second edition. Edinburgh: Forestry Commission.

Francis, J.K. (1986). The Relationship of Bole Diameters and Crown Widths of Seven Bottomland Hardwood Species. *USDA Forest Service Research Note SO-328*. Southern Forest Experiment Station.

Gadow, K. von (1996). Modelling growth in managed forests - realism and limits of lumping. *The Science of the Total Environment*, **183**, 167-177.

Gadow, K. von and Hui, G. (1999). *Modelling Forest Development*. Dordrecht: Kluwer Academic Publishers.

Gadow, K. von and Hui, G. (2002). Characterizing forest spatial structure and diversity. In L. Björk, (ed.), *Sustainable Forestry in Temperate Regions*. Proceedings of the SUFOR International Workshop April 7-9, 2002 in Lund, Sweden, pp. 20-30.

Gadow, K. von, Hui, G.Y., Chen, B.W. and Albert, M. (2003). Beziehungen zwischen *Winkelmaß* und Baumabständen. (Relationship between the *Winkelmaß* and nearest neighbor distances.) *Forstwissenschaftliches Centralblatt*, **122**, 127-137.

Gaffrey, D., Sloboda, B., Fabrika, M. and Šmelko, Š. (2001). Terrestrial single-image photogrammetry for measuring standing trees, as applied in the Dobroč virgin forest. *Journal of Forest Science*, **47**, 75-87.

Garrison, G.A. (1949). Uses and modifications for the "Moosehorn" crown closure estimator. *Journal of Forestry*, **47**, 733-735.

Gill, S. and Biging, G. (2002). Autoregressive moving average models of conifer crown profiles. *Journal of Agricultural, Biological and Environmental Statistics*, **7**, 558-573.

Gill, S.J., Biging, G.S. and Murphy, E.C. (2000). Modeling conifer tree crown radius and estimating canopy cover. *Forest Ecology and Management*, **126**, 405-416.

Gilmore, D.W. (2001). Equations to describe crown allometry of *Larix* require local validation. *Forest Ecology and Management*, **148**, 109-116.

Gilmore, D.W., Seymour, R.S. and Maguire, D.A. (1996). Foliage-sapwood area relationships for *Abies balsamea* in central Maine, USA. *Canadian Journal of Forest Research*, **26**, 2071-2079.

Greis, I. and Kellomäki, S. (1981). Crown structure and stem growth of Norway spruce undergrowth under varying shading. *Silva Fennica*, **15**, 306-322.

Groiser, D. (2006). *Spatial pattern of bark damage caused by grey squirrels on two research sites in Wales*. Diplomarbeit, Hochschule Für Angewandte Wissenschaft und Kunst, Fachhoschule Hildesheim/Holzminden/Göttingen, Fakultät Ressourcenmanagement Göttingen.

Hale, S. (2004). Managing Light to Enable Natural Regeneration in British Conifer Forests. *Forestry Commission Information Note 63*. Edinburgh: Forestry Commission.

Hamilton, G.J. (1969). The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. *Forestry*, **42**, 133-144.

Hamilton, G.J. (1975). Forest Mensuration Handbook. *Forestry Commission Booklet 39*. London: HMSO.

Hann, D.W. and Hanus, M.L. (2004). Evaluation of nonspatial approaches and equation forms used to predict tree crown recession. *Canadian Journal of Forest Research*, **34**, 1993-2003.

Hart, C. (1995). Alternative Silvicultural Systems to Clear Cutting in Britain: A Review. *Forestry Commission Bulletin 115*. London: HMSO.

Hasenauer, H. (1997). Dimensional relationships of open-grown trees in Austria. *Forest Ecology and Management*, **96**, 197-206.
Hasenauer, H. and Monserud, R.A. (1996). A crown ratio model for Austrian forests. *Forest Ecology and Management*, **84**, 49-60.
Hashimoto, R. (1991). Canopy development in young sugi (*Cryptomeria japonica*) stands in relation to changes with age in crown morphology and structure. *Tree Physiology*, **8**, 129-143.
Hegyi, F. (1974). A simulation model for managing jack-pine stands. In J. Fries, (ed.), *Growth Models for Tree and Stand Simulation*. Stockholm: Royal College of Forestry, pp. 74-90.
Henbo, Y., Itaya, A., Nishimura, N. and Yamamoto, S.-I. (2004). Long-term canopy dynamics in a large area of temperate old-growth beech (*Fagus crenata*) forest: analysis by aerial photographs and digital elevation models. *Journal of Ecology*, **92**, 945-953.
Hetherington, J.C. (1967a). A simple device for the measurement of the crown diameter of standing trees. *Commonwealth Forestry Review*, **46**, 5.
Hetherington, J.C. (1967b). Crown diameter: stem diameter relationships in managed stands of Sitka spruce. *Commonwealth Forestry Review*, **46**, 278-281.
Holdaway, M.R. (1986). Modeling tree crown ratio. *Forestry Chronicle*, **62**, 451-455.
Holdsworth, R.P., Curtis, J.D. and McCleary, D. (1936). The reflecting crownmeter. *Journal of Forestry*, **34**, 528-530.
Honer, T.G. (1971). Crown shape in open- and forest-grown balsam fir and black spruce. *Canadian Journal of Forest Research*, **1**, 203-207.
Horn, H.S. (1971). *The Adaptive Geometry of Trees*. Princeton: Princeton University Press.
Hui, G.Y. and Gadow, K. von (2002). Das Winkelmass: Herleitung des optimalen Standardwinkels. (The optimum standard angle of the Winkelmass.) *Allgemeine Forst- und Jagdzeitung*, **173**, 173-177.
Hussein, K.A. (2001). *Parameter-parsimonious Models for Crown and Stem Profiles*. PhD thesis, Faculty of Forest Sciences and Forest Ecology, Georg-August-University Göttingen.
Hussein, K.A., Albert, M. and Gadow, K. von (2000). The Crown Window - a simple device for measuring tree crowns. *Forstwissenschaftliches Centralblatt*, **119**, 43-50.
Hynynen, J. (1995). Predicting tree crown ratio for unthinned and thinned Scots pine stands. *Canadian Journal of Forest Research*, **25**, 57-62.
Ishii, H.T., Tanabe, S. and Hiura, T. (2004). Exploring the relationships among canopy structure, stand productivity, and biodiversity of temperature forest ecosystems. *Forest Science*, **50**, 342-355.
Jack, S.B. and Long, J.N. (1991). Analysis of stand density effects on canopy structure: a conceptual approach. *Trees: Structure and Function*, **5**, 44-49.
Jan., J.-F. (2005). Comparison of forest canopy height derived using lidar data and aerial photos. *Taiwan Journal of Forest Science*, **20**, 13-27.
Jereb, O. (1972). Correlation between the d.b.h. and crown diameter of *Picea abies*. *Erdo*, **21**, 57-61.
Kalliovirta, J. & Tokola, T. (2005). Functions for estimating stem diameter and tree age using tree height, crown width and existing stand database information. *Silva Fennica*, **39**, 227–248.
Kändler, G. (1986). Ermittlung von Bestandesparametern als Eingangsgrößen für Interzeptionsmodelle mit Hilfe aerophotogrammetrischer Verfahren. (Determining

stand parameters as entry values for interception models with the aid of aerophotogrammetric methods.) *Mitteilungen der Forstlichen Versuchs- und Forschungsanstalt Baden-Württemberg*, **127**.

Kantola, A. and Mäkelä, A. (2004). Crown development in Norway spruce [*Picea abies* (L.) Karst.]. *Trees: Structure and Function*, **18**, 408-421.

Koch, B. and Reidelstürz, P. (1998). Terrestrische Stereophotogrammetrie für forstliche Anwendungen. (Ground stereo photogrammetry for use in forestry.) *Allgemeine Forst Zeitschrift für Waldwirtschaft und Umweltvorsorge*, **53**, 1464-1467.

Kohyama, T., Hara, T. and Tadaki, Y. (1990). Patterns of trunk diameter, tree height and crown depth in crowded *Abies* stands. *Annals of Botany*, **65**, 567-574.

Koike, F. (1985). Reconstruction of two-dimensional tree and forest canopy profiles using photographs. *Journal of Applied Ecology*, **22**, 921-929.

Konecny, G. (2003). *Geoinformation: Remote Sensing, Photogrammetry and Geographic Information Systems*. London: Taylor & Francis.

Kozlowski, T.T. (1971a). *Growth and Development of Trees*. Volume 1. London: Academic Press.

Kozlowski, T.T. (1971b). *Growth and Development of Trees*. Volume 2. London: Academic Press.

Kozlowski, T.T., Kramer, P.J. and Pallardy, S.G. (1991). *The Physiological Ecology of Woody Plants*. San Diego: Academic Press.

Krajicek, J.E., Brinkman, K.A. and Gingrich, S.F. (1961). Crown competition - a measure of density. *Forest Science*, **7**, 35-42.

Kramer, H. (1966). Crown development in conifer stands in Scotland as influenced by initial spacing and subsequent thinning treatment. *Forestry*, **39**, 40-58.

Laar, A. van and Akça, A. (1997). *Forest Mensuration*. Göttingen: Cuvillier Verlag.

Liu, J., Burkhart, H.E. and Amateis, R.L. (1995). Projecting crown measures for loblolly pine trees using a generalized thinning response function. *Forest Science*, **41**, 43-53.

MacFarlane, D.W., Green, E.J., Brunner, A. and Amateis, R.L. (2003). Modeling loblolly pine canopy dynamics for a light capture model. *Forest Ecology and Management*, **173**, 145-168.

Maguire, D.A. and Hann, D.W. (1987). A stem dissection technique for dating branch mortality and reconstructing past crown recession. *Forest Science*, **33**, 858-871.

Maguire, D.A. and Hann, D.W. (1989). The relationship between gross crown dimensions and sapwood area at crown base in Douglas-fir. *Canadian Journal of Forest Research*, **19**, 557-565.

Maguire, D.A. and Hann, D.W. (1990). A sampling strategy for estimating past crown recession on temporary growth plots. *Forest Science*, **36**, 549-563.

Maguire, D.A., Kershaw, J.A., Jr. and Hann, D.W. (1991). Predicting the effects of silvicultural regime on branch size and crown wood core in Douglas-fir. *Forest Science*, **37**, 1409-1428.

Mäkelä, A. and Mäkinen, H. (2003). Generating 3D sawlogs with a process-based growth model. *Forest Ecology and Management*, **184**, 337-354.

Mäkinen, H., Ojansuu, R. and Niemistö, P. (2003a). Predicting external branch characteristics of planted silver birch (*Betula pendula* Roth.) on the basis of routine stand and tree measurements. *Forest Science*, **49**, 301-317.

Mäkinen, H., Ojansuu, R., Sairanen, P. and Yli-Kojola, H. (2003b). Predicting branch characteristics of Norway spruce (*Picea abies* (L.) Karst.) from simple stand and tree measurements. *Forestry*, **76**, 525-546.

Mason, B., Kerr, G. and Simpson, J. (1999). What is Continuous Cover Forestry? *Forestry Commission Information Note 29*. Edinburgh: Forestry Commission.

Matthews, J.D. (1963). Some applications of genetics and physiology in thinning. *Forestry*, **36**, 172-180.

Minor, C.O. (1951). Stem crown-diameter relation in southern pine. *Journal of Forestry*, **49**, 490-493.

Mitchell, K.J. (1975). Dynamics and Simulated Yield of Douglas-Fir. *Forest Science Monographs*, **17**.

Mizoue, N. and Masutani, T. (2003). Image analysis measure of crown condition, foliage biomass and stem growth relationships of *Chamaecyparis obtusa*. *Forest Ecology and Management*, **172**, 79-88.

Muth, C.C. and Bazzaz, F.A. (2003). Tree canopy displacement and neighborhood interactions. *Canadian Journal of Forest Research*, **33**, 1323-1330.

Nagel, J. (1999). Konzeptionelle Überlegungen zum schrittweisen Aufbau eines waldwachstumskundlichen Simulationssystems für Nordwestdeutschland. (Conceptual ideas for stepwise development of a simulation systems for forest growth models in northwest Germany.) *Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt*, **128**.

Nagel, J., Albert, M. and Schmidt, M. (2002). Das waldbauliche Prognose- und Entscheidungsmodell BWINPro 6.1 – Neuparametrisierung und Modellerweiterungen. (The silvicultural decision support system BWINPro 6.1 – new parameterisation and model extensions. *Forst und Holz*, **57**, 486-493.

Nakayama, H. and Nagashima, I. (1963). Studies on tree measurements by terrestrial photogrammetry: I. Tree crown diameter measurements by stereo-camera. *Bulletin of the Nagoya University Forests*, **3**, 1-12.

Nash, A.J. (1948). The Nash Scale for measuring tree crown widths. *Forestry Chronicle*, **24**, 117-120.

Oliver, C.D. and Larson, B.C. (1996). *Forest Stand Dynamics*. Update edition. New York: Wiley.

Osada, N., Tateno, R., Hyodo, F. and Takeda, H. (2004). Changes in crown architecture with tree height in two deciduous tree species: developmental constraints or plastic response to the competition for light? *Forest Ecology and Management*, **188**, 337-347.

Ottorini, J.-M., Goff, N. le and Cluzeau, C. (1996). Relationships between crown dimensions and stem development in *Fraxinus excelsior*. *Canadian Journal of Forest Research*, **26**, 394-401.

Pelt, R. van and Nadkarni, N.M. (2004). Development of canopy structure in *Pseudotsuga menziesii* forests in the southern Washington Cascades. *Forest Science*, **50**, 326-341.

Phattaralerphong, J. and Sinoquet, H. (2005). A method for 3D reconstruction of tree crown volume from photographs: assessment with 3D-digitized plants. *Tree Physiology*, **25**, 1229-1242.

Pommerening, A. (unpubl.). *Modelling the Growth of Sitka Spruce and Birch as Part of a Silvicultural Decision Support System for Continuous Cover Forestry: Interim Report 2002*. School of Agricultural and Forest Sciences, University of Wales, Bangor.

Pommerening, A. (2002). Approaches to quantifying forest structures. *Forestry*, **75**, 305-324.

Pommerening, A. and Wenk, G. (2002). Preliminary study for a flexible growth model to predict the consequences of CCF in Wales. In K. von Gadow *et al.*, (eds.), *Continuous Cover Forestry: Assessment, Analysis, Scenarios*. Dordrecht: Kluwer Academic Publishers, pp. 231-251.

Pretzsch, H. (1992). Modellierung der Kronenkonkurrenz von Fichte und Buche in Rein- und Mischbeständen. (Modelling the crown competition of Norway spruce and beech in pure and mixed stands.) *Allgemeine Forst- und Jagdzeitung*, **163**, 203-213.

Pretzsch, H., Biber, P. and Ďurský, J. (2002). The single tree-based stand simulator SILVA: construction, application and evaluation. *Forest Ecology and Management*, **162**, 3-21.

Pretzsch, H., and Ďurský, J. (2001). Evaluierung von Waldwachstumssimulatoren auf Baum- und Bestandesebene. (Evaluation of forest stand simulators on tree and stand level.) *Allgemeine Forst- und Jagdzeitung*, **172**, 146-150.

Prodan, M. (1951). *Messung der Waldbestände*. (Mensuration of Forest Stands.) Frankfurt: J.D. Sauerländer's Verlag.

Quine, C.P., Coutts, M.P., Gardiner, B.A. and Pyatt, D.G. (1995). Forests and Wind: Management to Minimise Damage. *Forestry Commission Bulletin 114*. London: HMSO.

Rautiainen, M. and Stenberg, P. (2005). Simplified tree crown model using standard forest mensuration data for Scots pine. *Agricultural and Forest Meteorology*, **128**, 123-129.

Reid, D.E.B., Lieffers, V.J. and Silins, U. (2004). Growth and crown efficiency of height repressed lodgepole pine; are suppressed trees more efficient? *Trees: Structure and Function*, **18**, 390-398.

Remphrey, W.R., Davidson, C.G. and Blouw, M.J. (1987). A classification and analysis of crown forms in green ash (*Fraxinus pennsylvanica*). *Canadian Journal of Botany*, **65**, 2188-2195.

Riedel, A. (2002). Einsatz der Mehrbildtriangulation zur strukturellen Analyse von Baumpflanzen. (Structural analysis of tree plants by means of photogrammetric triangulation.) *Forstarchiv*, **73**, 55-61.

Robinson, M.W. (1947). An instrument to measure forest crown cover. *Forestry Chronicle*, **23**, 222-225.

Roeh, R.L. and Maguire, D.A. (1997). Crown profile models based on branch attributes in coastal Douglas-fir. *Forest Ecology and Management*, **96**, 77-100.

Rollinson, T.J.D. (1988). Respacing Sitka spruce. *Forestry*, **61**, 1-22.

Rudnicki, M., Lieffers, V.J. and Silins, U. (2003). Stand structure governs the crown collisions of lodgepole pine. *Canadian Journal of Forest Research*, **33**, 1238-1244.

Rudnicki, M., Silins, U. and Lieffers, V.J. (2004). Crown cover is correlated with relative density, tree slenderness, and tree height in lodgepole pine. *Forest Science*, **50**, 356-363.

Schröder, J. and Gadow, K. von (1999). Testing a new competition index for maritime pine in northwestern Spain. *Canadian Journal of Forest Research*, **29**, 280-283.

Schröder, J., Gerold, D. and Röhle, H. (2005). Modellierung der Kronenbreite in BWINPro-S für die Anwendung in Strukturreichen Beständen. (Modelling crown width in BWINPro-S for use in structurally diverse stands.) In J. Nagel, (ed.), *Proceedings of the Deutscher Verband Forstlicher Forschunganstalten, Sektion Ertragskunde*, 9-11th May 2005, Freising, pp. 33-40.

Seifert, T. (2002). Personal communication. Chair of Forest Growth Sciences, Department of Ecosystem and Landscape Management, Weihenstephan Science Centre, Munich University of Technology, Am Hochanger 13, 85354 Freising, Germany.

Shepperd, W.D. (1973). An instrument for measuring tree crown width. *USDA Forest Service Research Note RM-229*. Rocky Mountain Forest and Range Experiment Station.

Short, E.A. and Burkhart, H.E. (1992). Predicting crown-height increment for thinned and unthinned loblolly pine plantations. *Forest Science*, **38**, 594-610.

Siemon, G.R., Wood, G.B. and Forrest, W.G. (1976). Effects of thinning on crown structure in radiata pine. *New Zealand Journal of Forestry Science*, **6**, 57-66.

Smith, J.H.G. and Bailey, G.R. (1964). Influence of stocking and stand density on crown widths of Douglas fir and lodgepole pine. *Commonwealth Forestry Review*, **43**, 243-246.

Smith, W.R. (1994). An empirical evaluation of a three-dimensional crown model for predicting volume growth. *Forest Ecology and Management*, **69**, 199-209.

Smith, W.R., Farrar, R.M., Jr., Murphy, P.A., Yeiser, J.L., Meldahl, R.S. and Kush, J.S. (1992). Crown and basal area relationships of open-grown southern pines for modeling competition and growth. *Canadian Journal of Forest Research*, **22**, 341-347.

Song, B., Chen, J. and Silbernagel, J. (2004). Three-dimensional canopy structure of an old-growth Douglas-fir forest. *Forest Science*, **50**, 376-386.

Spathelf, P. (2003). Reconstruction of crown length of Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.) - technique, establishment of sample methods and application in forest growth analysis. *Annals of Forest Science*, **60**, 833-842.

Spiecker, H., Hansen, J., Klimo, E., Skovsgaard, J.P., Sterba, H. and Teuffel, K. von (2004). Norway Spruce Conversion – Options and Consequences. *European Forest Institute Research Report 18*. Leiden: Brill.

Sprinz, P.T. and Burkhart, H.E. (1987). Relationships between tree crown, stem, and stand characteristics in unthinned loblolly pine plantations. *Canadian Journal of Forest Research*, **17**, 534-538.

Summers, R.W. and Proctor, R. (1999). Tree and cone selection by crossbills *Loxia* sp. and red squirrels *Sciurus vulgaris* at Abernethy forest, Strathspey. *Forest Ecology and Management*, **118**, 173-182.

Tabbush, P.M. and White, I.M.S. (1988). Canopy closure in Sitka spruce - the relationship between crown width and stem diameter for open grown trees. *Forestry*, **61**, 23-27.

Temesgen, H., LeMay, V. and Mitchell, S.J. (2005). Tree crown ratio models for multi-species and multi-layered stands of southeastern British Columbia. *Forestry Chronicle*, **81**, 133-141.

Turnock, W.J. and Ives, W.G.H. (1957). An instrument for measuring the radii of tree crowns. *Forestry Chronicle*, **33**, 355-357.

Umeki, K. (1995). Modeling the relationship between the asymmetry in crown display and local environment. *Ecological Modelling*, **82**, 11-20.

Valentine, H.T., Ludlow, A.R. and Furnival, G.M. (1994). Modeling crown rise in even-aged stands of Sitka spruce or loblolly pine. *Forest Ecology and Management*, **69**, 189-197.

Vanclay, J.K. (1994). *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests*. Wallingford: CAB International.

Vezina, P.E. (1962). Crown width-d.b.h. relationships for balsam fir and white spruce in Quebec. *Forestry Chronicle*, **38**, 463-473.

Vezina, P.E. (1963). More about the Crown Competition Factor. *Forestry Chronicle*, **39**, 313-317.

Ward, W.W. (1964). Live crown ratio and stand density in young, even-aged, red oak stands. *Forest Science*, **10**, 56-65.

Warrack, G.C. (1959). Crown dimension, initial diameter, and diameter growth in a juvenile stand of Douglas fir. *Forestry Chronicle*, **35**, 150-153.

Zagalikis, G., Cameron, A.D. and Miller, D.R. (2005). The application of digital photogrammetry and image analysis techniques to derive tree and stand characteristics. *Canadian Journal of Forest Research*, **35**, 1224-1237.

APPENDIX I - FIELDWORK PROTOCOLS

Crown Measurements

Tyfiant Coed Fieldwork Protocol, July 2003
Owen Davies

Data required

The following data are to be collected for each sample tree:

1. Diameter at breast height (*dbh*).
2. Total height (*h*). These data will be used, in combination with height to crown base, to determine crown length.
3. Height to crown base (*hcb*). The crown base is assumed to be the lowest contiguous live branch (see *Measurement of* h *and* hcb, below).
4. Maximum crown radius (r_{max}).

Equipment required

Research grade *dbh* tape, marked in 0.1 cm intervals
Haglöf Vertex III with transponder (and staff-mounted transponder)
Compass
30 m tape
Crown mirror densiometer
Sunscreen portable computer with batteries and pens

It may be expedient to carry spare batteries for the Vertex and its transponder and the Sunscreen and its pen, as well as pens and paper data sheets in case of computer failure.

Data collection

Measurement of dbh
Measurements of *dbh* should be made at 1.3 m above ground level, marked by a painted line on each tree, using a research grade diameter tape to give results accurate to the nearest 0.1 cm. In all cases the guidelines given in Forestry Commission Booklet 39 (Hamilton, 1975) and the *Tyfiant Coed* survey protocol should be followed.

Measurement of h *and* hcb
Two measurements of *h* and *hcb* should be made for each tree using the Haglöf Vertex III. Before making any measurements, the Vertex operator should view the sample tree from various angles until satisfied that the crown base has been correctly located. The crown base is taken to be the point at which the lowest live branch leaves the main stem, excluding epicormic and adventitious shoots and sparsely foliated branches not contiguous with the main part of the crown.

Once the crown base has been identified, the Vertex operator should locate positions from which to view the tree. The two sets of height measurements should be taken from opposite sides of the tree, i.e. separated by an angle of 180°. If the tree is leaning, measurements should be made perpendicular to the plane of the lean. If the tree is not leaning but is on sloping ground, measurements should be made across, rather than up or down, the slope. The Vertex operator should attempt to find a position along the chosen line roughly one to one and a half tree lengths away from the sample tree where the top and base of the tree and the crown base are visible. It is clearly difficult to fulfil all of these requirements, particularly in dense stands, but at the least it is important to ensure that the angle between the two sets of measurements is 180° (a compass should be used to check this if necessary) and that the angle of view to the top of the tree is roughly 45°.

Total height is considered to be the vertical distance between the top and base of the tree. Similarly, *hcb* is the vertical distance between the tree base and the crown base. The Vertex transponder should be placed at 1.3 m on the tree stem, as indicated by the *dbh* line, and the transponder height setting of the device entered accordingly. If the tree is leaning heavily, it may be necessary to position the transponder at 1.3 m vertically above the tree base rather than on the stem (using a staff-mounted transponder if required). Heights should be recorded to the nearest 0.1 m. If the difference between the two measurements of *h* or *hcb* on opposite sides of the tree exceeds 1 m the measurements should be repeated.

Measurement of r_{max}

Eight measurements of r_{max} should be made for each tree using a 30 m tape, compass and crown mirror densiometer. Measurements should be made along lines extending from the centre of the tree stem towards the eight major compass points. The tape should be secured to the tree stem so that the zero point is on a radius from the centre of the tree perpendicular to the line to be assessed; the tape should then run parallel to the line followed by the fieldworker, at a tangent to the stem surface. The fieldworker should stand with their back to the stem facing in the required direction as indicated by a compass bearing. Proceeding away from the tree stem, following the compass bearing, the fieldworker should sight upwards using the crown mirror densiometer. When, without deviating to either side of the required line, the crosshair of the mirror is aligned with the crown margin (see Ayhan (1977) for clarification), the fieldworker should read the crown radius from the tape level with their position to the nearest 0.05 m. For very small trees, sighting with the densiometer should not be necessary. Care in all cases must be taken to ensure that the desired bearing is properly identified and carefully followed.

Data recording

Data should be entered directly into an Excel spreadsheet using the Sunscreen portable computer. For each tree, identified by number, data to be recorded include *dbh* (to 0.1 cm), two measures of *h* (to 0.1 m, not to vary more than 1 m), two measures of *hcb* (to 0.1 m, not to vary more than 1 m), eight measures of r_{max} (to 0.05 m, each measure identified according to its bearing) and any relevant notes (e.g. position and length of any breaks in the crown, major irregularities in crown shape such as pronounced asymmetry, defoliation, felling damage). If a tree is randomly selected to replace another tree that is unsuitable for sampling, a note of the number of the replaced tree should be made.

References

Ayhan, H.O. (1977). A crown radius instrument. *Scottish Forestry*, **31**(2), 67-70.

Hamilton, G.J. (1975). Forest Mensuration Handbook. *Forestry Commission Booklet 39*. London: HMSO.

Crown Profile Assessments

Data collection for comparison of methods, using small (height < 4 m) sample trees

Tyfiant Coed Fieldwork Protocol, May 2005
Owen Davies

For accurate crown profile assessments, particularly photogrammetry, wind speeds must be minimal. Precipitation is likely to damage the digital camera or distort images. Good illumination is desirable, but glare may affect both photography and the use of the "crown window".

Sample tree selection

Sample trees should be less than 4 m in height, of good, straight form and with a single leader. Ideally, there should be no neighbouring trees or rank vegetation within 3-4 m so that the tree is clearly visible from all directions.

Data required

The following data are to be collected for each sample tree:

1. Diameter at breast height (*dbh*).
2. Total height (*h*) and height to crown base (*hcb*).
3. Maximum crown radius (r_{max}).
4. Two orthogonal "crown window" profiles.
5. Digital photographs for photogrammetry.

Equipment required

1.3 m staff
Small callipers, marked in 0.1 cm intervals
Haglöf Vertex III with transponder
Compass
30 m tape
"Crown window" with head rest, tripod, acetates, clips and permanent pens
Digital camera with spare flash card
3 ranging rods with tripods, ranging rod level and flagging tape
WeatherWriter clipboard with paper and pencil

Data collection

Measurement of dbh, h, hcb *and* r_{max}
Direct stem and crown measurements should be made as per the **Crown Measurements** fieldwork protocol, except that:

1. Sample trees will not be marked with a *dbh* line, and the 1.3 m staff or 30 m tape should be used to locate the breast height point.
2. *dbh* should be measured with callipers rather than a tape. Where the stem is irregular in cross-section an average should be taken of two orthogonal measurements.

3. The crown mirror densiometer is unlikely to be necessary for sighting the crown margins with such small sample trees.

"Crown window" profiles
The use of the "crown window" is described by Hussein *et al.* (2000). Profiles will be scaled according to measured crown length, so there is no need to record the distance between the crown window and the sample tree or the crown window and the user's eyes; although these distances can be varied between profiles as convenient, they must remain constant for a given profile. Two orthogonal profiles, checked with a compass, should be taken for each tree, with viewing directions chosen so that as far as possible the full vertical and horizontal extent of the crown is clearly visible. Once an acetate has been clipped firmly in place, the drawn profile should show the tip of the crown, the outline of the branches perpendicular to the viewing angle, and the point at which *hcb* was measured. A note should be made on the drawing of the tree identification and the approximate bearing of the viewing angle (N, NW, W etc.).

Digital photographs
Three ranging rods should be set up around each sample tree to provide reference points, scale and orientation for photogrammetry. Visibility permitting, the rods should be spaced equally around the tree just beyond the crown margin. One of the rods, marked with flagging tape, should be positioned due south of the tree's leader for orientation. Each rod should be vertical, checked with the ranging rod level, and held in place with a tripod. As far as possible, the 50 cm intervals on each rod should not be obscured by the tripod or by vegetation.

Eight photographs per tree, taken from a distance of 1-2 tree lengths at the cardinal and inter-cardinal points, should suffice in conditions of good visibility. Where viewing distances are limited by surrounding vegetation, it may be necessary to take multiple photographs from one point to cover the full vertical and horizontal extent of the crown; in this case, there should be substantial overlap between photographs. As many ranging rod reference points as possible should be visible in each photograph. Camera settings must match those used for calibration; maximum resolution (2272 x 1704 pixels) and either default or maximum zoom.

Data recording

The small quantities of data involved can be recorded manually. Crown window profile data should be recorded directly onto acetates as described above. For each tree, other data to be recorded include *dbh* (to 0.1 cm), two measures of *h* (to 0.1 m), two measures of *hcb* (to 0.1 m), eight measures of r_{max} (to 0.05 m, each measure identified according to its bearing) and any relevant notes. A diagram should be drawn of the directions from which photographs were taken for each tree, with photographs numbered in ascending order, and of ranging rod positions. It should be obvious from field notes in what order the trees were photographed, so that photographs can be matched to measured data after downloading. Weather conditions may also be noted.

Reference

Hussein, K.A., Albert, M. and Gadow, K. von (2000). The crown window – a simple device for measuring tree crowns. *Forstwissenschaftliches Centralblatt*, **119**(1-2), 43-50.

APPENDIX II - SCRIPTS, SPREADSHEETS & MACROS

Avenue script for crown profile measurement tool "StoreProfilePoint"

This tool was used to extract crown profile data from crown window images (see section 3.1.4). A mouse-click on an active theme in ArcView GIS 3.3 stored the name of the theme ("profile") and the X and Y co-ordinates of the cursor in the table "crownprofiles.dbf".

```
currentView = av.GetActiveDoc
currentTheme = currentView.GetThemes.Get(0).GetName
currentPoint = currentView.GetDisplay.ReturnUserPoint
currentX = currentPoint.GetX
currentY = currentPoint.GetY

profileVTab = av.GetProject.FindDoc("crownprofiles.dbf").GetVTab
profileField = profileVTab.FindField("profile")
XField = profileVTab.FindField("X")
YField = profileVTab.FindField("Y")

currentRecord = profileVTab.AddRecord
profileVTab.SetValue(profileField,currentRecord,currentTheme)
profileVTab.SetValue(XField,currentRecord,currentX)
profileVTab.SetValue(YField,currentRecord,currentY)
```

Excel spreadsheet and macro for generalised crown profiles

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	4.9	Ltotal (m)		4.6	Llight (m)		*Press Ctrl+w to calculate Llight*			0.1	*Measurement interval (m)*		
2	1.73	rmax (m)		0.3	Lshade (m)								
3													
4	Profile a left		Profile a right		Profile b left		Profile b right		Quadratic mean r (m)	Dtip (m)	Dbase (m)	Drmax (m)	Absolute Drmax (m)
5	r (m)	Dtip (m)	r (m)	Dtip (m)	r (m)	Dtip (m)	r (m)	Dtip (m)					
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	4.9	4.6	4.6
7	0.04	-0.10	0.04	-0.10	0.08	-0.10	0.01	-0.10	0.05	0.1	4.8	4.5	4.5
8	0.09	-0.20	0.06	-0.20	0.14	-0.20	0.05	-0.20	0.09	0.2	4.7	4.4	4.4
9	0.14	-0.30	0.09	-0.30	0.20	-0.30	0.08	-0.30	0.14	0.3	4.6	4.3	4.3
10	0.18	-0.40	0.13	-0.40	0.24	-0.40	0.16	-0.40	0.18	0.4	4.5	4.2	4.2

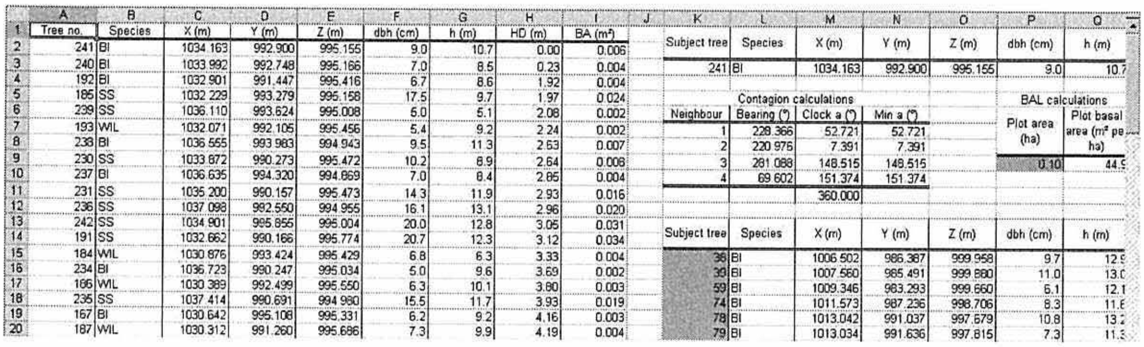
This spreadsheet was used to produce a single generalised crown profile for each tree (see section 3.1.4), taking as its inputs a measured total crown length value (L_{total}) and crown profile data (crown radius, r, and vertical distance from crown tip, D_{tip}) from the table "crownprofiles.dbf" for four half profiles. The following macro identified the D_{tip} of the maximum quadratic mean r to give light crown length (L_{light}):

```
Sub Calculate_Llight()
'
' Calculate_Llight Macro
' Macro recorded 31/03/2005 by Owen Davies
'
' Keyboard Shortcut: Ctrl+w
'
    ' Find rmax and associated Dtip/Llight value
    Range("A2").Activate
    Set rmax = ActiveCell
    With Range("I6:I56")
        Set Findrmax = .Find(rmax.Value, LookIn:=xlValues)
    End With
    Findrmax.Offset(0, 1).Activate
    Set Llight = ActiveCell
    Range("D1").Value = Llight

    ' Select and scroll to A1
    Range("A1").Activate
    ActiveWindow.ScrollRow = 1
    ActiveWindow.ScrollColumn = 1
End Sub
```

L_{total} and L_{light} were used to calculate shade crown length (L_{shade}), and L_{light} and L_{shade} were used to calculate vertical distance from the point of maximum crown radius ($Dr_{\max}$) for each measurement interval.

Excel spreadsheet and macro for calculating spatial variables



	A	B	C	D	E	F	G	H	I
1	Tree no.	Species	X (m)	Y (m)	Z (m)	dbh (cm)	h (m)	HD (m)	BA (m²)
2	241	BI	1034.163	992.900	995.155	9.0	10.7	0.00	0.006
3	240	BI	1033.992	992.748	995.166	7.0	8.5	0.23	0.004
4	192	BI	1032.901	991.447	995.416	6.7	8.6	1.92	0.004
5	185	SS	1032.229	993.279	995.158	17.5	9.7	1.97	0.024
6	239	SS	1036.110	993.624	995.008	6.0	5.1	2.08	0.002
7	193	WIL	1032.071	992.105	995.456	5.4	9.2	2.24	0.002
8	238	BI	1036.555	993.983	994.943	9.5	11.3	2.63	0.007
9	230	SS	1033.872	990.273	995.472	10.2	8.9	2.64	0.008
10	237	BI	1036.635	994.320	994.869	7.0	8.4	2.85	0.004
11	231	SS	1035.200	990.157	995.473	14.3	11.9	2.93	0.016
12	236	SS	1037.098	992.550	994.955	16.1	13.1	2.96	0.020
13	242	SS	1034.901	995.855	995.004	20.0	12.8	3.05	0.031
14	191	SS	1032.662	990.166	995.774	20.7	12.3	3.12	0.034
15	184	WIL	1030.876	993.424	995.429	6.8	6.3	3.33	0.004
16	234	BI	1036.723	990.247	995.034	5.0	9.6	3.69	0.002
17	186	WIL	1030.389	992.499	995.550	6.3	10.1	3.80	0.003
18	235	SS	1037.414	990.691	994.980	15.5	11.7	3.93	0.019
19	167	BI	1030.642	995.108	995.331	6.2	9.2	4.16	0.003
20	187	WIL	1030.312	991.260	995.686	7.3	9.9	4.19	0.004

Subject tree	Species	X (m)	Y (m)	Z (m)	dbh (cm)	h (m)
241	BI	1034.163	992.900	995.155	9.0	10.7

Contagion calculations			
Neighbour	Bearing (°)	Clock a (°)	Min a (°)
1	228.366	52.721	52.721
2	220.976	7.391	7.391
3	281.088	148.515	148.515
4	69.602	151.374	151.374
		360.000	

BAL calculations	
Plot area (ha)	Plot basal area (m² pe[illegible] ha)
0.10	44.[illegible]

Subject tree	Species	X (m)	Y (m)	Z (m)	dbh (cm)	h (m)
38	BI	1006.502	986.387	999.958	9.7	12.[illegible]
39	BI	1007.560	985.491	999.880	11.0	13.[illegible]
59	BI	1009.346	983.293	999.660	6.1	12.[illegible]
74	BI	1011.573	987.236	998.706	8.3	11.[illegible]
78	BI	1013.042	991.037	997.679	10.8	13.[illegible]
79	BI	1013.034	991.636	997.815	7.3	11.[illegible]

This spreadsheet was used to calculate all spatial variables apart from those based on height angle competitor selection (see section 3.5). A macro sorted the trees in the plot according to their horizontal distance from the subject tree (calculated using Pythagoras' theorem) and calculated values of the Hegyi index for 0.01 and 0.02 ha circular plots. Other spatial variables were calculated within the spreadsheet itself. The macro then copied values of spatial variables and pasted them into an output area of the spreadsheet (at lower right in the screenshot above) before proceeding to the next subject tree. The macro code is reproduced below:

```
Sub Calculate_Spatial_Data()
'
' Calculate_Spatial_Data Macro
' Macro recorded 14/01/2005 by Owen Davies
'
' Keyboard Shortcut: Ctrl+q
'
    Range("K15").Activate
    For Tree = 1 To 50
        ' Select subject tree from list
        Set TreeNo = ActiveCell

        ' Sort data by tree number
        Columns("A:I").Select
        Selection.Sort Key1:=Range("A2"), Order1:=xlAscending, _
            Header:=xlGuess, OrderCustom:=1, MatchCase:=False, _
            Orientation:=xlTopToBottom, DataOption1:=xlSortNormal

        ' Search and copy data for subject tree
        With Range("A2:A601")
            Set SelStart = .Find(TreeNo.Value)
```

```
    Set SelEnd = SelStart.Offset(0, 4)
    Range(SelStart, SelEnd).Select
    Selection.Copy
    Range("K3").Select
    Selection.PasteSpecial Paste:=xlPasteValues, _
        Operation:=xlNone, SkipBlanks:=False, Transpose:=False
End With

' Sort data by horizontal distance from subject tree
Columns("A:I").Select
Selection.Sort Key1:=Range("H2"), Order1:=xlAscending, _
    Header:=xlGuess, OrderCustom:=1, MatchCase:=False, _
    Orientation:=xlTopToBottom, DataOption1:=xlSortNormal

'Calculate Hegyi index (0.01 ha)
Hegyi1 = 0
For Neighbour = 1 To 100
    If Cells(2 + Neighbour, 8).Value > 5.64 Then
        Exit For
    End If
    Hegyi1 = Hegyi1 + ((Cells(2 + Neighbour, 6).Value / _
        Range("F2").Value) * (1 / Cells(2 + Neighbour, _
        8).Value))
Next
Range("AB3").Value = Hegyi1

'Calculate Hegyi index (0.02 ha)
Hegyi2 = 0
For Neighbour = 1 To 100
    If Cells(2 + Neighbour, 8).Value > 7.98 Then
        Exit For
    End If
    Hegyi2 = Hegyi2 + ((Cells(2 + Neighbour, 6).Value / _
        Range("F2").Value) * (1 / Cells(2 + Neighbour, _
        8).Value))
Next
Range("AC3").Value = Hegyi2

' Copy and paste calculated values for subject tree
Range("K3:AC3").Select
Selection.Copy
TreeNo.Select
Selection.PasteSpecial Paste:=xlPasteValues, _
    Operation:=xlNone, SkipBlanks:=False, Transpose:=False

' Step through list and check for valid subject tree number
TreeNo.Offset(1, 0).Activate
```

```
        If ActiveCell.Value < 1 Then
            Exit For
        End If
    Next

    ' Select and scroll to A1
    Range("A1").Activate
    ActiveWindow.ScrollRow = 1
    ActiveWindow.ScrollColumn = 1
End Sub
```

Most spatial variable calculations within the spreadsheet were relatively simple, for example counting the number of trees within a specific search radius or summing their basal areas. The uniform angle index, however, was more complicated to implement. Bearings from the subject tree to each of the four nearest neighbours were calculated based on X and Y co-ordinates and horizontal distances (cells L7:L10). The contents of cell L7, for example, are as follows:

```
=IF($C$3=$M$3,IF($D$3>$N$3,0,180),IF($D$3=$N$3,IF($C$3>$M$3,90,270),
IF($C$3>$M$3,IF($D$3>$N$3,DEGREES(ASIN(($C$3-$M$3)/$H$3)),
90+DEGREES(ASIN(($N$3-$D$3)/$H$3))),
IF($D$3<$N$3,180+DEGREES(ASIN(($M$3-$C$3)/$H$3)),
270+DEGREES(ASIN(($D$3-$N$3)/$H$3))))))
```

Here C3 and D3 are the X and Y co-ordinates of the neighbour, M3 and N3 are the co-ordinates of the subject tree, and H3 is the horizontal distance between the two trees. After first establishing whether the trees shared an X or Y co-ordinate (which would place the neighbour in one of the four cardinal directions relative to the subject tree), the formula identified the quadrant in which the neighbour lay by comparing co-ordinates, then calculated the exact bearing by trigonometry.

The angles between each neighbour and the next neighbour clockwise were then calculated (cells M7:M10):

```
=IF(L7=MIN(L$7:L$10),MIN(L8,L9,L10)-L7,
IF(L7=MAX(L$7:L$10),360-(L7-MIN(L8,L9,L10)),
IF(AND(L7<L8,L7<L9),MIN(L8,L9)-L7,IF(AND(L7<L8,L7<L10),MIN(L8,L10)-L7,
IF(AND(L7<L9,L7<L10),MIN(L9,L10)-L7,IF(AND(L7>L8,L7>L9),L10-L7,
IF(AND(L7>L8,L7>L10),L9-L7,L8-L7)))))))
```

This formula (from cell M7) established the clockwise order of the neighbours according to their bearings (cells L7:L10), then subtracted the bearing of the current neighbour from that of the next neighbour clockwise, except where the current neighbour was at the highest bearing, in which case the calculated angle was subtracted from 360°.

The formula for the uniform angle index specifies that it should be calculated based on the smallest angles between each pair of neighbours (see section 3.5.1), so any angles greater than 180° were subtracted from 360° (cells N7:N10). These angles were then compared with the reference angle of 72° in cell S3 to complete the calculation of the index (cf. equation 3.42 in section 3.5.1):

```
=(IF($N$7<72,1,0)+IF($N$8<72,1,0)+IF($N$9<72,1,0)+IF($N$10<72,1,0))/4
```

A similar combination of spreadsheet and macro was used for height angle competitor selection:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Tree no.	Species	X (m)	Y (m)	Z (m)	dbh (cm)	h (m)	HD (m)	Height angle	Height angle + >dbh	BA (m²)	Hegyi		Subject tree	Species	X (m)	Y (m)
2	264	SS	931.907	1086.830	995.601	25.0	24.4	0.00	1	0	0.049	#DIV/0!		264	SS	931.907	1086.83
3	262	SS	933.897	1083.827	995.847	33.2	25.2	3.60	1	1	0.087	0.369					
4	263	SS	934.180	1089.743	995.719	25.1	24.7	3.69	1	1	0.049	0.272		75.0	Angle (°)		
5	266	SS	927.554	1086.816	995.219	45.6	29.8	4.35	1	1	0.163	0.419		0.00	Proportion of subject tree height		
6	267	SS	928.414	1091.258	995.271	26.7	24.7	5.64	1	1	0.056	0.189		*Press Ctrl+Shift+q to calculate competition indices*			
7	260	SS	938.105	1085.289	996.065	45.5	30.6	6.39	1	1	0.163	0.285					
8	265	SS	930.666	1094.110	995.399	38.0	32.0	7.39	1	1	0.113	0.206		Subject tree	Species	X (m)	Y (m)
9	219	SS	932.729	1079.189	995.743	27.8	25.1	7.69	0	0	0.061	0.145					
10	216	SS	936.748	1079.345	996.079	30.4	25.2	8.91	0	0	0.073	0.136		38	SS	986.186	1017.521
11	268	SS	923.444	1089.806	995.036	31.7	26.3	8.97	0	0	0.079	0.141		41	SS	981.533	1025.231
12	261	SS	937.836	1093.957	995.974	44.3	26.4	9.27	0	0	0.154	0.191		47	SS	968.718	1018.90
13	258	SS	941.333	1088.139	996.355	27.1	25.2	9.52	0	0	0.058	0.114		50	SS	962.708	1025.02
14	221	SS	926.354	1078.025	995.191	37.1	27.2	10.41	0	0	0.108	0.143		54	SS	958.364	1029.60
15	269	SS	923.287	1094.311	994.941	44.5	29.8	11.41	0	0	0.156	0.156		55	SS	952.341	1020.84

For each subject tree, once the macro had sorted neighbours according to horizontal distance, the following formula (from cell I3) was used to determine whether each neighbour could be considered a competitor:

```
=IF(G3+E3<TAN(RADIANS($N$4))*H3+($T$2*$N$5)+$R$2,0,1)
```

Here G3 and E3 are the height and Z co-ordinate of the neighbour tree respectively, N4 is the height angle (75°), H3 is the horizontal distance between subject and neighbour trees, T2 is the subject tree height, N5 is the proportion of subject tree height from which the search cone extends (0), and R2 is the subject tree Z co-ordinate (cf. equation 3.47 in section 3.5.3). A result of unity indicated that the neighbour was a competitor.

Note that the inclusion of the proportion of subject tree height from which the search cone extended meant that this point could be shifted from the tree base to a height approximating the crown base or point of maximum crown radius, but that, owing to the limitations imposed on competitor selection by relatively narrow buffer strips, this feature was not used.

Competitors were counted and their basal areas were summed. Column J was used to determine whether competitors also had larger stem diameters than the subject tree (indicated by a result of unity in the following formula, from cell J3), so that the basal area of larger trees could be calculated accordingly:

```
=IF(AND(I3=1,F3>$S$2),1,0)
```

Here a value of unity in I3 indicates that the neighbour is a competitor, F3 is the *dbh* of the neighbour tree and S2 is the *dbh* of the subject tree.

Values of the Hegyi index were calculated directly in this spreadsheet, rather than via the macro. Column L was used to calculate the contribution of each neighbour tree to the index using the following formula (from cell L3); these values were then summed only for trees identified as competitors:

```
=(F3/$S$2)*(1/H3)
```

Here F3 and S2 are neighbour and subject tree *dbh* respectively, and H3 is the horizontal distance between the trees (cf. equation 3.46 in section 3.5.3).

The incorporation of all variable calculations into the spreadsheet meant that the macro was relatively simple in this case, being concerned solely with sorting neighbours according to horizontal distances, and copying and pasting output values for each subject tree.