A METHOD TO DESCRIBE THE THREE DIMENSIONAL BRANCHING CHARACTERISTICS OF SITKA SPRUCE

(*Picea sitchensis* Bong. Carr.)

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ABSTRACT OF THESIS

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A model for computing the three-dimensional (3-D) crown architecture of Sitka spruce (*Picea sitchensis* Bong. Carr.) was developed. This method, which we call 3-D SITKA, is based on adopting the approach of a previous model developed by Casella & Sinoquet (2003).
The overall objectives of this study were: (i) to apply the multi-scale biometric methodology proposed by Casella and Sinoquet (2003), based on topological and geometrical information to deal with the 3-D architecture of tall Sitka spruce (*Picea sitchensis* Bong. Carr.) trees, (ii) to develop an empirical 3-D SITKA Canopy Architecture model, and (iii) to evaluate the model quality.
27 trees, from three experimental forest sites in Scotland, were assessed by measuring dbh, tree height, number of whorls (live and dead) Crown depth and crown length. 81 branches were measured in terms of their lengths, insertion angles and diameter. 54 of the 81 branches were then described in details.
Empirical allometric relationships were described with polynomial, asymmetric sigmoid or power functions to parameterise and/or describe morphological units of the plant, topological relationships and geometry. The results in general were satisfactory.

The 3-D SITKA model, based on a detailed set of empirical relationships performed from field measurements, recreates significantly the three-dimensional plant entities distribution within space. However, canopy structure has shown clear difference within the experimental sites in terms of their contrasting characteristics.

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Contents	

Literature review paper

A REVIEW OF TREE CANOPY ARCHITECTURE: MODELS AND OBSERVATIONS

1. INTRODUCTION

The importance of branch modelling is associated with its potential uses. There is a wide range of factors with which many studies in branchiness are linked. Collin & Houllier (1992) stressed some of these factors such as giving a better description to the role of crown compartment in growth yield studies as well as its role in understanding and estimating the decline in forests. Secondly, the need for organizing the industrial operation such as harvesting or logging which are influenced by limb size. In addition, the importance of assessing the effect of silvicultural practices on timber quality that depends, according to some studies, on knottiness (Collin & Houllier, 1992).

In this study we try to establish a methodology that can be used in the future as input to process based model which can predict and visualize the 3-D architecture of Sitka spruce (*Picea sitchensis* Bong. Carr.) by using the same principles as Casella & Sinoquet (2003) for Poplar (*Populus* spp.) in their 3-D CPCA model. We examine the relations between measured parameters to find whether it is possible to develop a model that has a potential use in determining other information of interest such as growth process, light interception, etc...

The overall objectives of this study were to: (i) apply the proposed multi-scale biometric methodology developed by Casella and Sinoquet (2003), based on topological and geometrical information to deal with the 3-D architecture of tall Sitka spruce (*Picea sitchensis* Bong. Carr.) trees, (ii) develop an empirical 3-D SITKA Canopy Architecture model, and (iii) evaluate the model quality.

Sitka spruce Picea sitchensis (Bong.) Carr.

The reason we studied Sitka spruce was its importance in the United Kingdom as a source of timber. This importance is associated with the fact that Sitka spruce provides over the half of the total volume of timber produced in Great Britain. The mild oceanic climate of western Britain leads to fast growth rate (Gardiner, 2002).

The name of Sitka spruce has originally derived from Sitka in Alaska although its natural range is all along the coast of North West America. It was introduced to the UK in 1831 and is, therefore, a non native conifer. The tree trunk grows in a very straight conical shape. It can grow up to 50 m or more in height with a trunk over 2m in diameter. Its bark distinguished by its colour which is greyish brown which gets curved fissures and flaky plates as it grows.

The needles grow individually and they are flattened and stiff, hard and very sharp. The flowers are red but it is very rare to be seen since they are usually found right at the top of the older trees before they develop to pale brown, blunt and domed cones which carry the seeds inside (Forestry Commission, website).

It has a very fast growth rate compared to some other trees, which means it can produce high volumes of timber in a comparatively short time. Models have been developed for growth or yield (Edwards and Christie, 1981). The "yield class" figure is the mean cubic metres growth, for each hectare of tree species for each year's growth. Sitka spruce has a range from 10 to 24 m^3 /ha/year.

The wood from this species is of high quality. It is very multipurpose and is easy to work with. Thinned trees are particularly valuable for paper making as the white colour of the wood and long cellulose fibres make strong but smooth paper. The major use of Sitka spruce wood in Britain is house construction, pallets and then paper (Forestry Commission, website).

2. Possible applications of branch modelling

Depending on the information of interest and study objects, many studies about branchiness and branch modeling, in general, have varied in terms of their approaches, techniques and methodologies. A number of studies discussed branch growth characteristics on this species as well as other species using different approaches by building geometrical or allometrical relationships to describe correlations between given growth parameters which affect or contribute to the crown architecture as we will discuss that in this chapter.

2.1- Light interception, photosynthesis and transpiration models

There are a number of studies discussed the use of crown structure models to forecast light absorbed by trees canopy from the level of a stand to the level of one tree and trees parts. We shall cite two examples of such models:

1- MAESTRO is a model which has been used widely for predicting light levels in stands. In a study by Wang Y. P. and Jarvis G. (1990) it was found that the total area of leaves and their spatial distribution within the crown are much more important than either crown shape or leaf inclination angle distribution in Sitka spruce. According to the research, this agrees with previous simulation studies at the canopy scale (see Jarvis and Leverenz, 1982). The total area of leaves within the crown is important for determining the physical and physiological processes of the canopy. It is less clear whether the leaf area density (LAD) distribution within the crown is important.

The same study showed the importance of adding detailed descriptions of these additional crown structural properties to MAESTRO as it correctly simulated daily amounts of photosynthetically active radiation PAR absorption, photosynthesis, and transpiration.

2- RATP: The model RATP (radiation, absorption, transpiration and photosynthesis) was used by Sinoquet *et al* (2001) to simulate the spatial distribution of carbon gain and water loss within canopies as a function of the spatial distribution of leaf area, distinguishing a number of foliage components. These features give the model a wide range of applications. On one hand, the model can be applied to a range of vegetation canopies from grasslands to forests. On the other hand, the model can be used to study resource partitioning between vegetation components, for example, species in intercropping, agroforestry or savanna systems, weeds and crops, individuals in heterogeneous canopies, and components within a plant. Sinoquet *et al*. (2001) attempted to test the RATP model at a shoot or branch scale, i.e. fine intracanopy scale. Model outputs were compared with data obtained from field. The result was that the model simulated adequately the intracrown distribution of radiation regime, transpiration and photosynthetic rates, at shoot or branch scales (Sinoquet *et al*. 2001).

The focus on branch modeling is meant to be a useful tool to serve several purposes that can be of importance for scientific and industrial interests.

It could be used to validate and analyse any reconstruction method to identify the relevant growth parameters and define the minimum data set to be measured in the field to feed the model (Casella & Sinquet, 2003).

2.3 - Rainfall interception.

Gash (1979). His analytical model is able to estimate the evaporation of rainfall intercepted by forest canopies from the forest structure, the mean evaporation and rainfall rates, and the rainfall pattern. In 1999 this model was reformulated by Gash, *et al* (1999). it was obvious that reformulating the analytical model as well as calculating the mean evaporation rate so that the evaporation rate per unit ground area decreceases as the canopy cover falls.

2.4- In addition to that, wind speed estimation is another aspect for which branching models could be useful (Daudet *et al*. 1999). Many studies have discussed the fractal modeling and how can the geometrical observations help in predict some other physiological process such as fluid movement within vessels (West B. *et al* 1999). The data acquired by this study can provide a real chance to validate such models that can be used for further uses in the future.

2.5- Growth models. A number of models have been used to predict the growth of either individual trees or stands. The behaviour of some these models have even proved to be satisfactory. One of these models is PipeQual which has been devolved by University of Helsinki. Another growth model developed by Pretzsch *et al* (2002) is SILVA which is a distance-dependent, age-independent individual-based growth model for pure and mixed forest stands. Dynamics of a stand either pure or mixed forests can be simulated by SILVA using a time step of five years. In every time step, SILVA can calculate growth, mortality, management, and regeneration of the single trees calculated (Schmid *et al*, 2006).

Hein *et al*, 2007 tried to develop models to predict the branching characteristics of Norway spruce but the models were initially set up to be used in integration with forest growth and yield simulation system even though the models outputs were applicable to be used for branchiness modeling.

3. Previous works on branch modelling

In the previous section we discussed some examples of models and mentioned some studies that tried to develop models that can be used to predict some variables of growth and branching process by measuring some parameters of the main stem and branches but multi-scale measurements like from the main trunk level to needles level in order to predict not only growth and yield of forests but also the other variables like biomass estimation. Only few studies discussed the possibility of achieving such targets among of which a study by Casella and Sinoquet, (2003) from which our methodology and model approach were adapted, as it will be discussed in the empirical paper of the dissertation. Here we will try to discuss the importance and influence of parameters used in our study.

3.1 Tree diameter

There is no doubt about the significance of tree diameter from many points of view. Many models have already used the (dbh) of trees, as a parameter in an equation, to predict other values since the measurement of (dbh) easier in many cases. Schroder *et al*, (2007) mentioned that tree size might be a variable more practical and more often available than tree age for growth models in mixed stands. According to the same study, Juvenile growth in oak is already being modeled based on dimension (dbh). In addition to that, Schroder *et al*, 2007 and by using BWINpr0 simulator calculated crown width by non-linear model based on diameter at breast height; height of crown base depends on height, (dbh), and stand top height. (dbh) can be predicted for an individual tree or on stand level it can be described as a function of tree height, stand and site properties (Fahlvik & Nnystrom, 2006).

3.2 Tree height

Tree height is a key variable which is useful for estimating stand volume and site quality as well as for describing stand vertical structure. Measuring tree heights is, however, costly (e.g. Temesgen & Gadow, 2004). Estimating this variable with a satisfactory accuracy is rather desirable. Parker, (1995) stressed that in general the light environment brightens decreases with increasing tree height within a forest, because taller trees are less abundant in the forest. The function diameter to tree height has been studied as a key function that can be used to generate models to predict other values. The relationships between height-Diameter at Breast Height (dbh), crown diameter to (dbh) and crown diameter to height were examined for Lebanon cedars (*Cedrus libani* A. Rich.) by Mahmut *et al*, (2005). That study concluded that the height to (dbh) and crown diameter to (dbh) relationships can be described by a power model, while the crown diameter-height relationship can be described by a S-curve model and heights and crown diameters can be predicted from (dbh), which can be easily calculated.

3.3 Crown diameter

On the level of individual trees, tree crown diameter can be used to describe competition between trees and since it is related to branch thickness, it also can affect timber quality (Condésa & Sterbab, 2005), and accordingly, the economic value of a tree. On the level of the stand management, it is of real importance estimate for a number of key factors that effect stand management (Pretzsch *et al*., 2002). In both studies, as in others, crown width can be calculated as a function of either (dbh) or tree height and (dbh).

3.4 Crown length

In most of many forest inventories the crown length is recorded as a parameter. Crown length is also used in models to predict the value of trees as well as an independent variable in volume equations (e.g. Douglas fir in the Northeast of the US). In addition, crown length has been considered to be an indicator of thinning reaction. Thinning slows down crown decline and thus leads to longer crowns than in unthinned stands (Spathelf, 2003).

3.5 Number of whorl branches

Collin & Houllier, (1992) in their study on Norway spruce proved what earlier studies on branching have revealed that there is a strong relationship between the length of the annual growth unit and its branches number which means that the latter can be predicted using the annual growth unit. What is more, the relationship between these two parameters is not influenced by the stage of the development and eventually tree age (e.g. Grace J. *et al* 1999). However, Cochrane & Ford, (1978) did not have the same within their sampled Sitka spruce trees but they mentioned that when a stand hierarchy is established after 'crown interlock', larger trees produce more branches and the correlation becomes significant.

In the case of Sitka spruce again, Achim A. *et al*, (2006) using a nonlinear model, made it clear that the number of whorl branches is quite constant along the main trunk. Hein *et al*, (2007) in a study on Norway spruce and by using mixed models revealed that the number of branches decreases with increasing height/diameter ratio. The latter, according to the authors, is known to be strongly related to the available resources for trees and forest density. Similar findings were obtained by Kantola A. *et al*, (2007) using the growth model "PipeQual" for Norway spruce.

3.6 Branch diameter

Some studies showed that the diameter of branches was strongly linked to the distance from the stem apex, (dbh) and crown depth, the more thick and long crowned trees are, the more thick their branches will be (e.g. Mäkinen *et al*. 2003). Within the crown, branch diameter tends to increase rapidly in the upper part of the crown with increasing distance from the stem apex. While in the middle part of the crown, this increase in distance slows down and branch diameter again slightly decreases on moving towards the crown base. These results were reported by other studies (e.g. Colin and Houllier, 1992) for Norway spruce.

Branch diameter adjoining to the stem increases rapidly during the first few years of the growth and then becomes approximately constant (Grace J. *et al* 1999). For *Pinus radiata* D. Don. For Sitka spruce, it has been proved by Achim A. *et al*, 2006 that the average diameters of whorl and inter-whorl branches modelled in that study are very similar to those modelled by Colin & Houllier (1992).

Kantola A. *et al*, (2007) recorded, for Norway spruce by PipeQual, the diameters of branches both measured and predicted increased at the upper third of the crown, then stabilised and finally decreased below the living crown and the largest branches were at the middle of the stem.

3.7 Branch length

For Norway spruce an empirical analysis shows that the ratio of branch length to canopy depth at the branch base is largest in the top of the crown, and gradually levels off deeper in the canopy (Kantola A. *et al*, 2007).

3.8 Branch insertion angle

According to Collin & Houllier, 1992, on Norway spruce, the insertion angle is influenced by the tree height growth rate. For given trees with the same height, trees which grow quickly have less growth units and the branch angles are smaller.

For Scots pine *Pinus sylvestris* L., Mäkinen & Colin, (1998), recorded that branch insertion angle is related to the whorl number and stem diameter. Similar findings were reported again by Mäkinen *et al*, 2003 on Silver Birch (*Betula pendula* Roth.) using multivariate models for branch angle. So, the branch angle increases quite rapidly in the top of the crown and then this increase slow down in the lower part of the stem. This difference along the stem was reported to be smaller for Sitka spruce Achim A. *et al*, (2006) who related this difference to knot straightness. Hence, Sitka spruce has straighter knots than Norway spruce and black spruce (*Picea mariana* {Mill.} B. S. P.).

3.9 Branch location

According to Collin & Houllier, (1992) on Norway spruce, the location of the whorl branches is determined by upper scale scars position. The whorl position can be roughly predicted if the height growth curve is obtained. To the same source, whorl branches are attached to the stem in area of 20 % of the annual shoot length.

These nine parameters mentioned above, in addition to what they are related or influenced by, can be obtained or predicted, as we showed above, using different approaches that might serve the purpose for which models are usually developed. Yet, these measures were only on the level of the main stem, the level of the branches (here we mean only the main branch and not its sub growth components), or both levels. During literature review we came across a number of good examples of models and modelling approaches. The reason we did not mention many other aspects or growth parameters is that we try to concentrate on parameters which, we believe, can help us in estimating topological and geometrical information that might help 3-D architecture of large Sitka spruce trees.

4. Recent studies on Sitka spruce

As we have already shown, it seems that studies which focused on understanding topological and geometrical information to deal with the 3-D architecture of large Sitka spruce trees are few indeed. However, some studies and models are assumed to be, according to their authors, valid for extrapolation. Collin & Houllier, 1992, reported their models to be applicable for Sitka spruce and this is what one of the most recent studies did try. Achim A. *et al*, 2006 developed a model which uses non-linear equations to describe the changes in branch characteristics along the stem. Based on Colin & Houllier (1992) models, the shapes of these equations were used with adjustments on the basis of what was reported and published information on the branching habits of Sitka spruce by Cannell 1974; Cochrane & Ford (1978).

Therefore, it is worth to shed some light on the study of the Achim *et al*, (2006). The main objective of the study was to predict the branching characteristics of Sitka spruce the models were made as a part of the development of a timber properties simulation tool. As it has been mentioned non-linear modelling was used to describe the average number of branches and their associated diameter, insertion angle, and probability of being alive for each annual growth unit. An adequate depiction of the branching properties was given by these non-linear equations.

5. Conclusion

In general, the reviewed literature about branching and branch modelling was useful in terms of understanding the possible relations between individual trees components, taking into account differences between species, approaches and other factors which might determine these relations. Nevertheless, a study based on a multi-scale description for the geometry and the seasonal dynamic of forest tree species is desirable (as it is discussed in the experimental paper. To address this challenge, an alternative approach (Casella and Sinoquet 2003) was to conceptualise the underlying plant architecture and use it as a guide for model construction and data acquisition. Based on the multi-scale decomposition of plant architecture into larger or smaller components (Godin *et al*. 1999), we propose then to measure a large and detailed number of parameters to explain accurately elementary units of temperate forest trees, their topological relationships and geometry (e.g., branch attributes from trunk dbh).

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Experimental Paper

A THREE DIMMENTIONAL CANOPY ARCHITECTURE MODEL FOR SITKA SPRUCE

(*Picea sitchensis* Bong. Carr.)

1. INTRODUCTION

Leaf area density and its attributes (i.e., locations, orientations, sizes and shapes) are key canopy parameters needed to describe the radiation regime within a tree crown for simulating the mass and energy exchange between a canopy and the atmosphere (Whang and Jarvis 1990a, Takenaka 1994, Casella and Sinoquet 2007). A substantial range of models simulating mass and energy exchange between plants and the atmosphere have been developed with varying levels of complexity (Ross 1981, Whang and Jarvis 1990b, Law *et al*. 2001, Sinoquet *et al*. 2001).

The main difference between those models is the treatment of the canopy architecture. Because it is traditionally difficult to estimate the spatial distribution of leaf area within a canopy, the representation of the vegetation has generally been simplified. In the turbid medium approach (Ross 1981), canopies have been abstracted as a "leaf gas" and have been subdivided in horizontal layers with uniform spatial distributions of the foliage.

But, in case of horizontal and/or vertical heterogeneous or discontinuous canopies characterised by narrowly or widely spaced plants, those one-dimensional models are unsuitable (Whang and Jarvis 1990a, Law *et al*. 2001, Casella and Sinoquet 2007). For these situations, highest resolutions on the architectural description of canopies can be obtained via three different approaches: (i) as a collection of individual crowns modelled as 3-D geometrical shapes (Law *et al*. 2001), (ii) by modelling the 3-D architecture of a population of plants using stochastic (De Reffye *et al*. 1988), fractals (Chen *et al* 1994) or L-systems (Prusinkiewicz 1986) methods, or (iii) by describing accurately the geometry of each plant in situ, using the sophisticated 3-D digitising method (Sinoquet and Rivet 1997).

The first approach has been successful in heterogeneous open-canopy forest landscape systems (Law *et al*. 2001). Nevertheless, this effort to consider the spatial heterogeneity of a canopy based on crown envelopes remain fundamentally one-dimensional at the crown or at the plot scales since the LAD within each foliage envelope is assumed to be uniformly distributed. The three next approaches based on stochastic, fractals or L-systems theories improved largely the 3-D canopy architecture resolution since they integrated both topological (Hallé *et al*. 1978) and geometrical (Ross 1981) notions of plant architecture.

Introducing stem, branch and leaf characteristics and/or growth rules, abstracted (but often oversimplified by some assumptions) from field measurements and observations, the architecture of a population of plants was then stochastically generated from virtual plants by the modelling operation (Chen *et al*. 1994). Nevertheless, despite that all of these methods can approximate many species shapes for studying light-vegetation interactions, to our knowledge, model outputs have never been precisely compared with field measurements (e.g., canopy openness). To solve this missing link, a precise description of the 3-D organisation of every plant entity in space (i.e., from internode–leaf) can be reach through the digitising method, which only deals with the 3-D plant geometry. Unfortunately, the application of this last method could not be fulfilled for describing the geometry and the seasonal dynamic of forest tree spp. because of their complex structure.

To address this challenge, an alternative approach was to conceptualise the underlying plant architecture and use it as a guide for model construction and data acquisition (after e.g., Casella and Sinoquet 2003). Based on the multi-scale decomposition of a plant architecture into larger or smaller components (Godin *et al*. 1999) we propose then to measure a large and detailed number of parameters to explain accurately elementary units of temperate forest trees, their topological relationships and geometry (e.g., branch attributes from trunk *dbh*).

The objectives of this study were to: (i) apply the proposed multi-scale biometric methodology developed by Casella and Sinoquet (2003), based on topological and geometrical information to deal with the 3-D architecture of tall Sitka spruce (*Picea sitchensis* Bong. Carr.) trees, (ii) develop an empirical 3-D SITKA Canopy Architecture model, and (iii) evaluate the model quality.

2. MATERIAL AND METHODS

2.1 Plant material

The study tries to identify the relationship between branch structures. Measurements were carried out during spring 2007 in three forest sites. Three harvesting sites were chosen in conjunction with James Jones and Sons harvesting department. Table 1 indicates each of the site factors in relation to this study.

Table 1 Site factors

Location	Grid Ref	Age	Av Top Ht	Vol/ha	Av Vol/tree	Av DBH	Stems /ha	Tariff No	No of Trees	Total Vol	Area (ha)
Castlemilk	NY214860	38	22.9	627m3	0.3692	22	1700	34	17,680	6527.5	10.4
Ryes	NX907621	50	26.5	511	0.82	31	623	34	2,940	2860.98	5.6
Isles	NX878617	48	28.3	419	0.672	31.7	525	36	3,489	1975.68	15.7

2.2 Description of plant topology and geometry

Based on the definition of the multi-scale decomposition of a plant, trees were described in terms of components (axis, A; growth unit, U and metamer, M) and elementary units (internode, I; and needle, N). On one trunk (A1), axes of order 2 (A2) were branches connected to A1 and axes of order *n* (A*n*) were sub-branches connected to A*n*-1 (Figure 1). Each A*n* was described as a succession of growth units (U) and each U was described as a succession of metameric elements (M), themselves defined as internode units (I) bounded at their two extremities by nodes. Each node consists of an A*n* or a needle (N) (Figure 1).

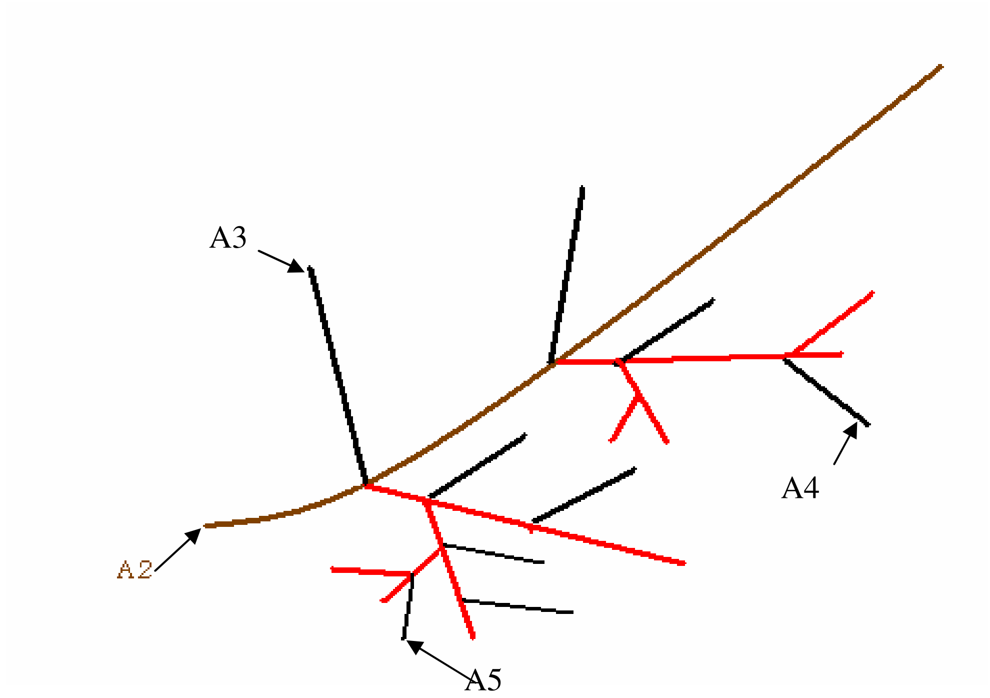


Figure 1. Multi-scale codification of a Sitka branch.

Following the plant topology definition, 3-D plant architecture can be computer-generated if each elementary unit of the plant is referred to a shape, a size, an orientation and a location in space. Basic 3-D geometric models (e.g., cylinder, frustum of a cone) are used to represent the shape (i.e., external surface) and the size of various plant units (e.g., height, l; base radius, $\frac{1}{2}\cdot d_b$ and top radius, $\frac{1}{2}\cdot d_t$ of a frustum of a cone). In our study, axes were represented as conic frustums and needles as cylinders.

Finally, the representation of a basic geometric model in the scene refers to its position (i.e., orientation and location) with respect to a global 3-D reference system ($\vec{i_0}$, $\vec{j_0}$, $\vec{k_0}$). To achieve this, we used a vector analysis approach. For an A2, its position in space is defined by the axial direction of $\vec{i_1}$ (i.e., the direction of the axis of symmetry of the frustum of a cone) and the co-ordinates (x, y, z) of its origin (i.e., the point of attachment of A2 to the trunk). ($\vec{i_1}$, $\vec{j_1}$, $\vec{k_1}$) being the local 3-D reference system of A2.

2.3 Model description

3-D SITKA starts to calculate the trunk height (lA1) from its *dbh*, as:

$$lA1 = f(dbh) \quad (1)$$

and the position of the first whorl (Whorl_z) displaying alive branches (the distance between A2 within a given whorl was assumed negligible) on A1, given by:

$$\text{Whorl}_z = f(lA1) \quad (2)$$

The number of whorl (nWhorl) within the tree crown is calculated from lA1 as:

$$n\text{Whorl} = f(lA1) \quad (3)$$

and the position of each consecutive whorl ($\text{Whorl}n_z$) within the A1, given by:

$$\text{Whorl}n_z = f\left(\frac{n}{n\text{Whorl}}\right) \quad (4)$$

The number of branches (nA2) for a given whorl (the branch mortality within the crown was assumed negligible) is calculated as:

$$nA2 = f\left(\frac{\text{Whorl}_z}{lA1}\right) \quad (5)$$

The modelling process calculates the length of every branch (lA2) carried by each whorl, as:

$$lA2 = f\left(\frac{\text{Whorl}_z}{lA1}\right) \quad (6)$$

and represented in the vegetative scene by its basal diameter (dA2) value, given by:

$$dA2 = f(lA2) \tag{7}$$

The final position and orientation of A2 are obtained after calculating their elevation (φA2) and azimuth (θA2) angle values as:

$$\varphi A2 = f\left(\frac{\text{Whorl}_z}{lA1}\right) \tag{8}$$

$$\theta A2 = \theta A2n\text{-}1 + \delta A2 \tag{9}$$

with $\theta A2_1$ = *rand* [0 ; 360°] and where δA2 = 360/nA2 is the branch divergence angle.
At last, 3-D SITKA completes the A2 reconstruction by describing the needle distribution along each growth unit (U). For each of them, the model computes their position and orientation according to values in internode and needle length (lI = 0.1 and lN = 1 cm, respectively), elevation (φN = 30^o) and divergence angle (δN = 45^o).
Following equations 2–9, An are, in their turn, reconstructed at metamer level, parameterised from field measurements. 3-D SITKA outputs are a collection of geometric objects.

2.4 Biometric measurements

Following the 3-D SITKA model description, a multi-scale biometric sampling approach was proposed to parameterise, at each order level, all equations (1–9) detailed above.
Within each of the three sites, nine trees were selected. The trees were randomly selected according to dominance class (dominant, co-dominant, sub-dominant). The trees were representative to the sites in terms of their crown condition. The architecture and branches distribution on the main trunk from each site can be used as a good sample of the stands.

Measurements

Before felling, the trees were given a unique identifiable code to distinguish between the three dominance classes. The diameter at breast height (dbh) was recorded on each of the sample trees. The bases of the trees were marked with spray paint to match the felled tree with its corresponding stump.

Trees felling

A total of 27 trees were selected with 9 trees from each site and 3 trees from each dominance class. Trees were cut by using a purpose built harvester.

- **Field measurements**

After felling, a series of measurements were taken to map the tree characteristics.

The first measurement was to record the total height of the tree using a standard loggers tape. The total number of the whorls on the main trunk was recorded including the current years growth. The crown height was recorded as the height between the top of the tree and the lowest whorl with ¾ live branches.

The middle point on the stem between the base of the tree and the lowest live whorl was also recorded as a reference point. The crown width was also measured to give an indication to the crown mass.

Whorls level assessment

Three whorls between the lowest live and the top whorl were selected for detailed examination. The whorls were selected by equally dividing the distance in the crown to give an even examination of the crown structure. The top whorl was selected approximately 30-50cm from the top of the tree to allow for more substantial material to be examined.

After selecting whorls on the main trunk, the following measurements were taken

1. Number of branches.
2. Length of all the branches on the whorls.
3. The average diameter of every branch by taking two readings and recording the average.
4. The insertion angle of every branch on the main trunk.
5. After recording the above data the branches were cut and weighted.
6. The condition of the branch whether it is a live, dead or broken.

7. From every whorl only one branch was selected and then labeled. The label refers to site name, tree number and class and the whorl position.
8. The acquired data is recorded on waterproof papers and transferred to separate Excel sheet only for field measurements.

- **The lab measurements**

Total number of (81) branches were collected. However, due to time restrictions only 54 branches were measured representing each of Castlemilk and Isles sites. The diameter and total length of the branch were the first parameters to measure. After these initial measurements in the lab definitions and measurements were established to describe the creation of a model.

Axis1 (A1) is the main trunk or the bole whose measurements were previously explained and on which A2 is the selected branch.

After that on A2 we have assumed that A3, A4, A5 and A6, if found, are symmetric on each node within the measured branch. Therefore, on each node on A2 one side was described in details (the red lines in fig 1 as an example) and these details are:

For A2 and A3 the following measurements were taken.

1- Length in centimeters.
2- Insertion angle.
3- Diameters (by taking the average between two readings).
4- Live, dead or broken.
5- If there are needles or not.
6- Nodes positions, on A3, from which A4 is originating and the relative position of these nodes.

   The node position is measured for the base of a given order or axis and all nodes were recorded including the nodes which have no axis were recorded but in every case a notice of the branches loss was considered and given the Zero value under the Axis number column.

Measurements on A4, A5 and A6

The same observations and parameters were recorded excluding diameters.

Measurements on the needle level

This procedure was undertaken before the other measurements in the lab and it was done as follow:

From every branch five segments are chosen (five orders). The needles on these orders are detached and next measurements were additionally taken:

-The total weight of the needle from the selected order was recorded.

-The average weight of ten needles.

-The average length of ten needles.

- Tracking data namely: site name, tree number, whorl position and the axis (order) number from which the needle are taken

The following is an example to a practical measurement on a branch

1. Take a branch from the sample.
2. Record the label data on the branch in an Excel sheet directly this sheet is for needle data only.
3. Start by preceding the needle measurements.
4. Take the length and the diameter of the A2 and count how many nodes on A2
5. Measure the distance from the base to the first node and then to the next node until the last node.
6. On the first node record how many A3 (four of occasions we had three A3 orders but in most cases they are only two). For both A3 orders measure the diameter, length and insertion angle.

   Select one A3 order on this node and start describing in details by measuring its length, diameter, insertion angle, and node positions and describe the further orders on this A3 order.
7. Repeat the same process on all nodes on A2 until the branch is described.

The required equipment for field measurements

- Calliper
- Measurement tape for diameters
- Logger tape
- Weighing scale or balance to weigh the fresh cut branches
- Labels

- Bags to carry branches
- Waterproof field note papers
- Paints (three different colours).
- See Appendices 1, 2 for field measurement forum and equipment used.

As we stressed above that one of our assumptions is that the branches are symmetric. Hence, by following this procedure, the half of a branch is measured literally in details while the other half is measured in terms of the lengths and insertion angles. This was applied on all orders on that branch.

In addition to that, the inter nodes growth axis were counted and an average of their length was recorded.

The time constraints I mentioned above were due to the unanticipated detailing in taking field and lab measurements. Fact is that the time available for my current study was not enough to process all branches since they needed more than five weeks and this simply because that high proportion of them reached large size and they had a big number of sub-orders.

2.5 Empirical functions and random deviation

From the results of the biometric measurements detailed above, empirical allometric relationships have been described with polynomial, asymmetric sigmoid or power functions to parameterise and/or describe morphological units of the plant, topological relationships and geometry. The shape of the regression model was chosen according to the form of the experimental data distribution, the best-fit value of the correlation coefficient of the adjustment (r^2) and a satisfactory random distribution of the residues (i.e., pass the SIGN test and/or the RUNS test). However, since completely controlled patterns would be disturbed by environmental factors, a random deviation ω was applied to selected empirical relationships (e.g., Equation 5) and constants to be more realistic, and was calculated as:

$$\omega = rand\,[-i\,;+i], \qquad (10)$$

where i is the standard deviation (SD) of a mean or the maximal or the average standard error (SE) of a constant pattern or of an empirical function, respectively.

2.6 Plants computer-generated images

Virtual plant images were computer-generated from the 3-D SITKA model outputs with the POV-Ray™ graphics software programme (Persistent of Vision™ Raytracer, *v.* 3.6). POV-Ray™ is a ray-tracing freeware (available at: *www.povray.org*) devoted to image synthesis, which allows definitions of elements of a scene from numerous shapes and textures. The vegetation scene was built from the POV-Ray™ file format generated by the 3-D SITKA model. The syntax used to define axes and needles was as below (after Casella and Sinoquet, 2003):

$$\text{object \{Needle\_cone scale} < l\text{N}, \tfrac{1}{2}\cdot d_b\text{N}, \tfrac{1}{2}\cdot d_t\text{N} > \text{rotate} < 0, \varphi\text{N}, \theta\text{N} > \quad \text{translate} < x, y, z > \text{texture\{ Needle\_texture \} \}} \tag{11}$$

Each object or element of the scene was scaled to the appropriate geometrical dimensions of its corresponding allocated shape (e.g., height, l; base radius, $\frac{1}{2}\cdot d_b$ and top radius, $\frac{1}{2}\cdot d_t$ of a frustum of a cone). The object was then rotated and translated according to the 3-D SITKA generated data for its orientation and location in the scene, respectively. A specific texture was finally given to each object, describing its colour. The resulting virtual tree could then be looked at from any point of view, after having placed virtual camera and light source in the scene. The light source (i.e., single and defined as direct sunbeams) was located at a large distance from the scene to the zenith.

3. RESULTS

3.1 Model parameterisation

A strong linear relationship explained the correlation between parameters and sine the final objective is to establish a method, which has the potential to be used for branch modelling. Some of these empirical relationships were established on different levels of the trees. Following are examples of our findings.

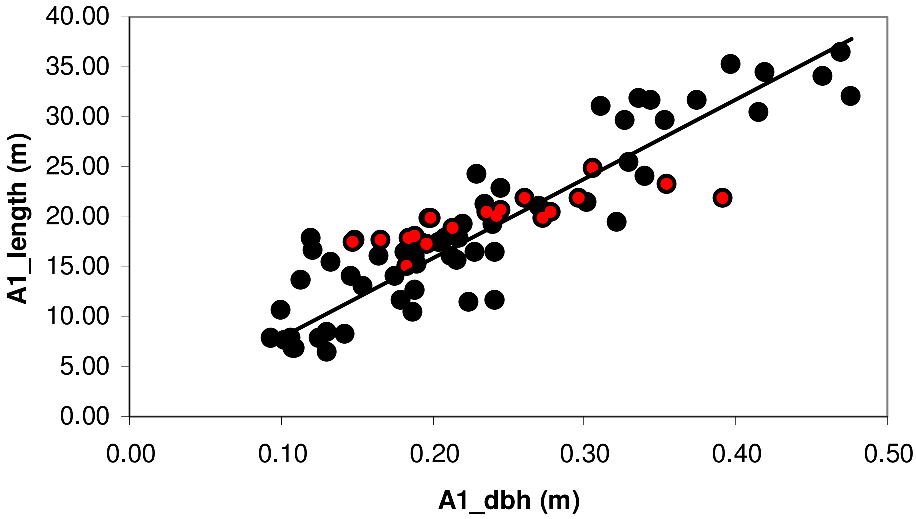


Figure 2. Tree height (*l*A1) versus tree *dbh* (Equation 1). Red points are data recorded in this study and black ones from Achim and Gardiner (2005). $y = 79.6\,x$, $r^2 = 0.78$.

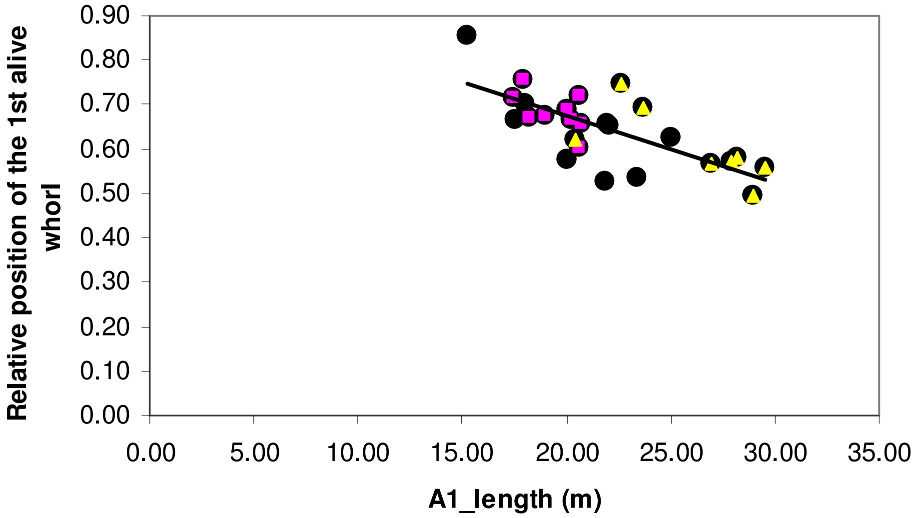


Figure 3. Relative position of the first live whorl on A1 versus its height (Equation 2). In black: Ryes, yellow: Isles and purple: Castlemilk. $y = -0.015\ x + 0.98$, $r^2 = 0.52$, $n = 27$.

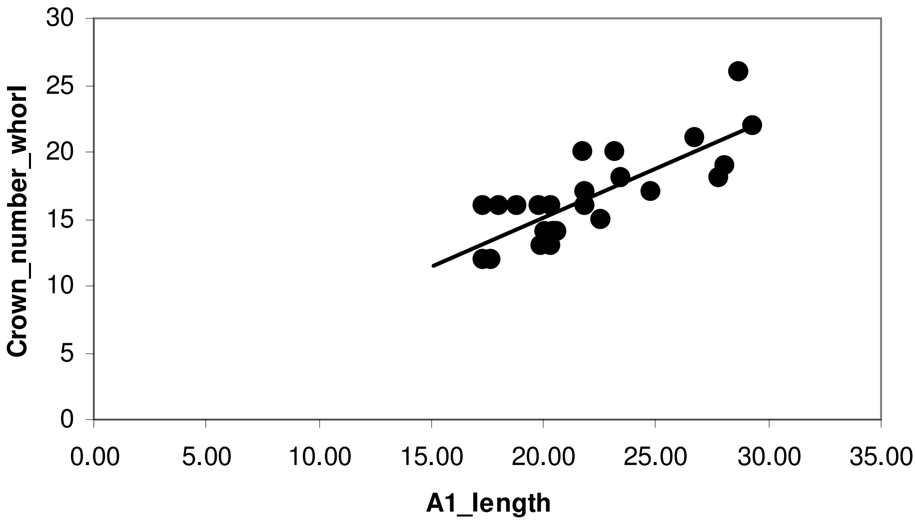
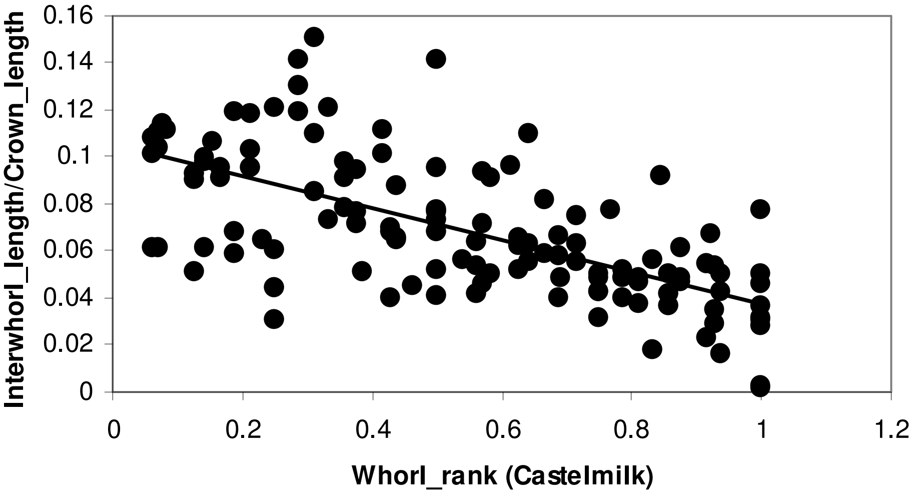
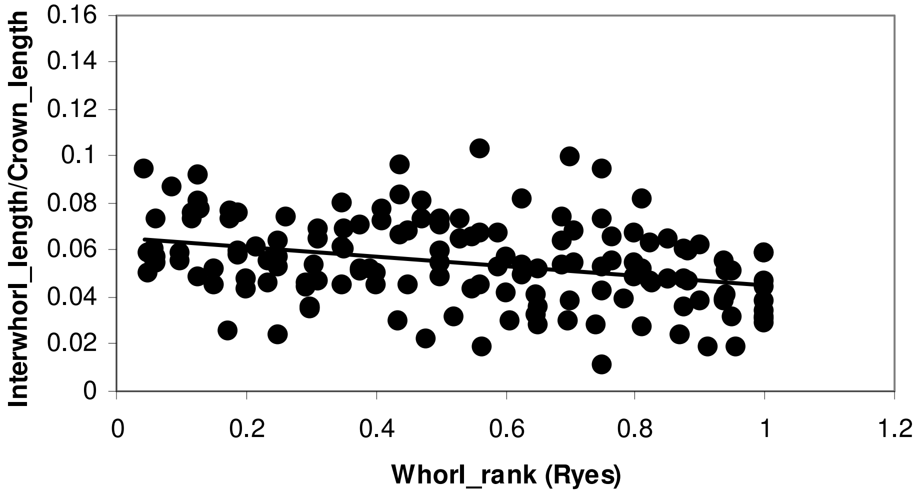


Figure 4. Number of whorl (*n*Whorl) versus the tree height (*l*A1) (Equation 3). $y = 0.74\ x + 0.39$, $r^2 = 0.63$, $n = 27$.





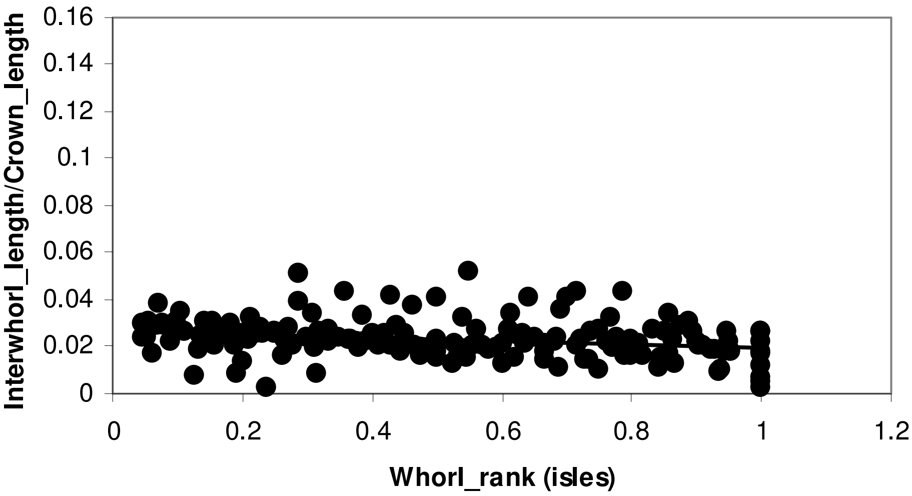


Figure 5. Interwhorl length versus the relative whorl rank on A1 for the forest sites Castlemilk (y = -0.068 x + 0.11, r^2 = 0.42,), Ryes (y = -0.021 x + 0.07, r^2 = 0.11,), and Isles (y = -0.007 x + 0.03, r^2 = 0.06,) (Equation 4).

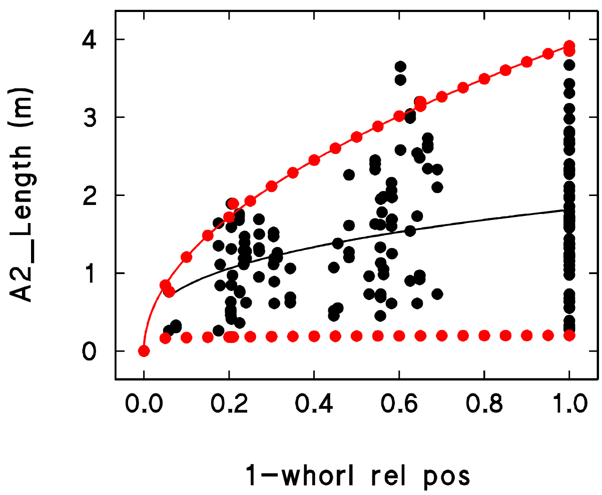


Figure 6. Branch length (*l*A2) versus the relative position of the whorl within the tree crown (Equation 6).

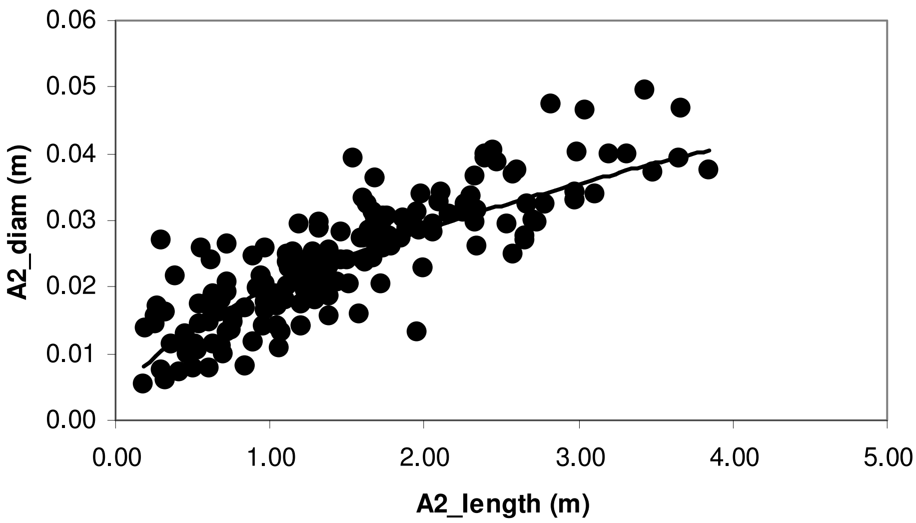
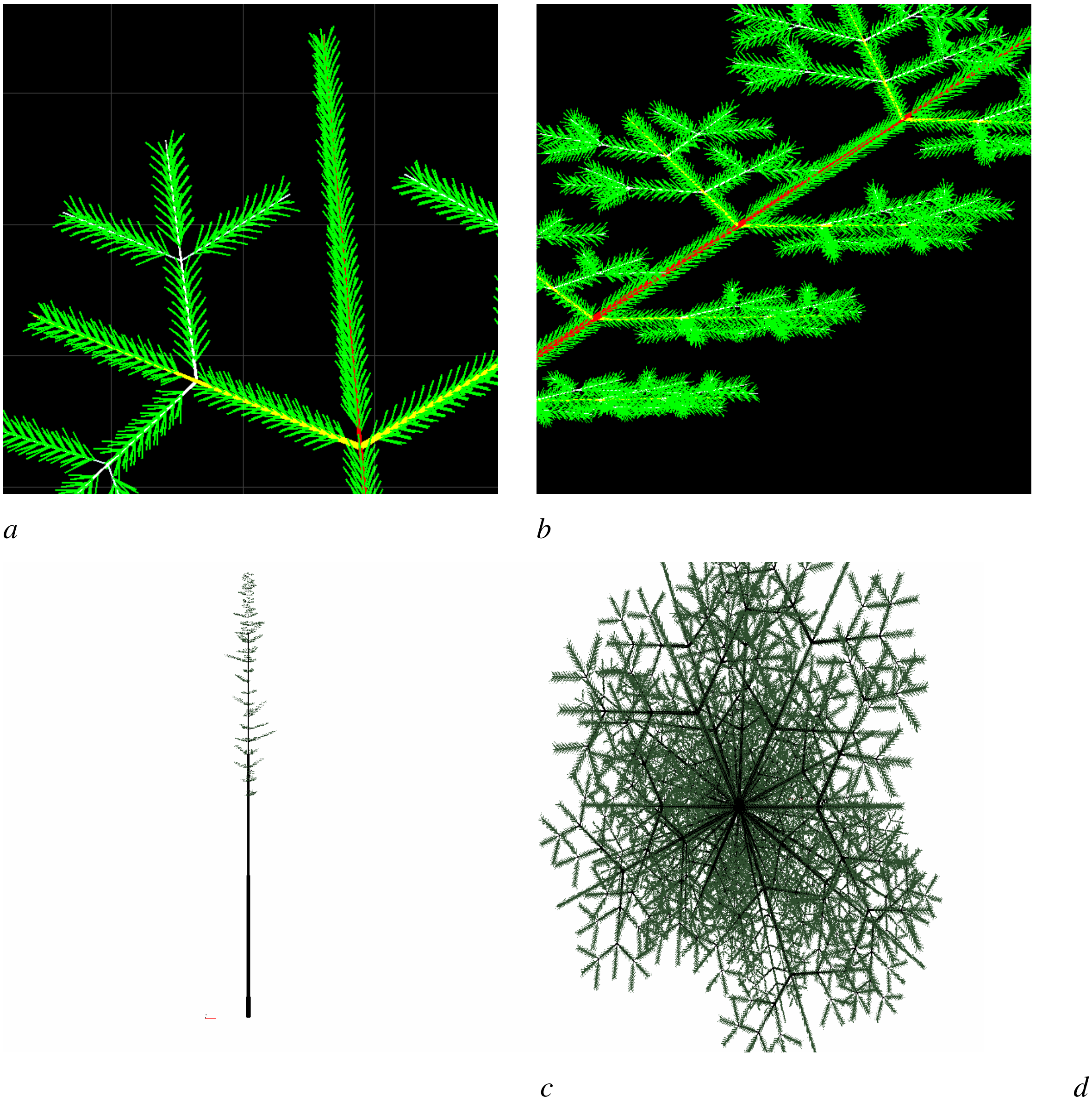


Figure 7. Branches diameter (*d*A2) versus *l*A2 (Equation 7). $y = 0.02\,x^{0.53}$, $r^2 = 0.64$,

3.2 Model outputs

The quality of the spatial distributions of every plant entity in a scene is shown by the synthesised images on the Figure 8. Results from the 3-D SITKA model process seem to recreate significantly the geometry of a branch to the more complex structure of a crown.



a *b* *c* *d*

Figure 8. Examples of virtual images, computer-generated from the 3-D SITKA model outputs by the Pov-Ray™ software for a 30-m height Sitka spruce tree. Bottom branch (a and b), south to the north (c) and top-down (d) views.

4. DISCUSSION

4.1 Reconstruction method

The present study proposes a method to reconstruct the 3-D plant architecture of Sitka spruce from an intensive set of allometric rules, derived from a hierarchical sampling in the field. Similar approaches have been proposed to study the space occupation by pine trees (Whitehead *et al*. 1990), and make 3-D plant mock-ups for botanical and landscape purposes. The 3-D reconstruction methods allow one to generate plant mock-ups with the same topological and geometrical properties as the plant population, where the architectural rules have been established. From these virtual 3-D reconstruction, the quality of the spatial leaf area distribution was qualitatively (visually) assessed by the comparison between virtual pictures and real photographs at branch scale. Reconstruction methods usually do not deal with the reconstruction of a given plant in the population. Moreover, as reconstruction methods use a sequence of empirical relationships, which show uncertainty, one can question the quality of the resulting plant. This is the reason why the assessment of the reconstruction quality should be a necessary step in these methods.

4.2 Reflections on the study

This study was a great opportunity to learn about conducting research on forest growth modelling, timber quality predictions, and branchiness models. A great deal of literature reviewed was supporting in terms of discussing different approaches, methods and observations. In addition, the practical assessment and building the model was another chance of great importance since it enabled me to find relations between growth parameters. Such relation would have several implications, which would become initial rules for understanding branchiness in Sitka spruce, of course in addition and combination to what already have been proposed by other studies. However, because time was a limiting factor for this study, not all the sampled branches and achieved data could be fully analysed. Moreover, we can predict from our achieved data sets that site factors (e.g., tinning regime) will strongly affect the crown architectural characteristics of the trees.

5. CONCLUSION

The 3-D SITKA model, based in a detailed set of empirical relationships performed from field measurements, recreates significantly the three-dimensional plant entities distribution within space. However, the selected experimental sites displayed markedly different canopy structure as a result of their contrasting characteristics (Table 1).

The next step would be: (1) to assess the quality of virtual Sitka spruce canopies for space occupation. Previous comparisons have been qualitative (e.g. Sinoquet and Rivet 1997), i.e., visual comparisons between plant photographs and computer-generated images, or quantitative (e.g. Casella and Sinoquet 2003), i.e. the comparison of variables computed from the photographs. The quantitative evaluation of 3-D plant mock-ups will be more satisfactory for two reasons: first, despite that we used a large set of reconstruction rules, in order to increase the reconstruction quality, reconstructed plants will not match a given real plant (i.e., when the plants in the virtual canopy will not visually match the plants seen in a real photographs, see Casella and Sinoquet 2003), as reconstruction rules are generic to all plants in the population where the architectural rules have been established. Second, a quantitative assessment of reconstruction quality allows one to evaluate the effect of combining several empirical rules. The criterion can be used to refine the set of architectural rules, and to identify the main architectural parameters which determine the 3-D space occupation. (2) To evaluate simplified reconstruction methods (i.e. by replacing some rules by assumptions; e.g., constant internode length), and then to define the minimum data sets to be measured in the field for a given reconstruction quality.

From a methodological point of view, the 3-D SITKA model is likely to find a number of applications: i) It could be used to validate any reconstruction method to identify the relevant growth parameters and define the minimum data set to be measured in the field to feed the model (Casella & Sinquet, 2007). ii) Since our new method expresses the spatial geometry of branches and needles of trees, it could be used as a valid contribution to 3-D models which deal with the distribution of light interception (e.g., RATP, MAESTRO).

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7. Appendices

Appendix 1 Field assessment forum

Location		Date	
Mean D.B.H (cm)		Top height (m)	

Tree No.		Tree diameter (cm)		Tree length (m)	
Crown depth (m)		Crown width (m)		Stump length (m)	
No. of live whorls			No. of dead whorls		

Diameter between D.B.H and last live whorl (cm)	
Height between D.B.H and last live whorl (m)	

Whorl No.	Whorl position	**T**op / **M**iddle	Whorl No.	Whorl position	**T**op/**M**iddle
	from top **cm**	**B**ottom		from top (cm)	**B**ottom
1			11		
2			12		
3			13		
4			14		
5			15		
6			16		
7			17		
8			18		
9			19		
10			20		

Top Whorl			Insertion		
Branch No.	Length (m)	Diameter (cm)	angle	weight (Kg)	Cut Y/N
1					
2					
3					
4					
5					
6					

Middle Whorl			Insertion		
Branch No.	Length (m)	Diameter (cm)	angle	weight (Kg)	Cut Y/N
1					
2					
3					
4					
5					
6					

Bottom Whorl			Insertion		
Branch No.	Length (m)	Diameter (cm)	angle	weight (Kg)	Cut Y/N
1					
2					
3					
4					
5					

6					

Comments ____

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Appendix 2. Measurement Equipments

Appendix 3 – 3-D SITKA Code in Fortran 90

```
c         3D - SITKA CANOPY ARCHITECTURE v.1 (FIRST DRAFT) 1-8-2007
c
c         MOHAMED OMAR (1) and ERIC CASELLA(2)
c
c         (1)
c         (2) Forest Research, Biometrics, UK - eric.casella@forestry.gsi.gov.uk
c
          integer CAM, Choice(10), Number_A1, Whorl
          integer A1_number_whorl, Crown_number_whorl, Whorl_number_A2
          integer A1, A2, A3, A4, A5, A6
          integer Node_A2, A2_number_nodes
          integer Node_A3, A3_number_nodes
          integer Node_A4, A4_number_nodes
          integer Node_A5, A5_number_nodes
          integer Node_A6, A6_number_nodes

          real CAMOX, CAMOY, CAMOZ, CAMVX, CAMVY, CAMVZ
          real a(50), b(50), c(50), d(50), e(50), f(50), g(50), h(50)
          real A1_x(50), A1_y(50), A1_z(50), pi
          real A1_dbh(50), A1_length(50), A1_radius(50)
          real Whorl_x, Whorl_y, Whorl_z
          real A2_diam, A2_radius, A2_length, MIN_A2_length, MAX_A2_length
          real A2_elevation, A2_azim, A2_phyllo
          real Correction1, A1_cum_iwhorl_length, A1_iwhorl_length
          real Node_x, Node_y, Node_z, Node2_rel_pos
          real A_x, A_y, A_z, B_x, B_y, B_z, x, y, z
          real A3_x, A3_y, A3_z, B3_x, B3_y, B3_z, x_3, y_3, z_3
          real Node3_x, Node3_y, Node3_z, Node3_rel_pos
          real A3_diam, A3_radius, A3_length, MIN_A3_length, MAX_A3_length
          real A3_elevation, A3_azim, A3_phyllo
          real A4_x, A4_y, A4_z, B4_x, B4_y, B4_z, x_4, y_4, z_4
          real Node4_x, Node4_y, Node4_z, Node4_rel_pos
          real A4_diam, A4_radius, A4_length, MIN_A4_length, MAX_A4_length
          real A4_elevation, A4_azim, A4_phyllo
          real A5_x, A5_y, A5_z, B5_x, B5_y, B5_z, x_5, y_5, z_5
          real Node5_x, Node5_y, Node5_z, Node5_rel_pos
          real A5_diam, A5_radius, A5_length, MIN_A5_length, MAX_A5_length
          real A5_elevation, A5_azim, A5_phyllo
          real A6_x, A6_y, A6_z, B6_x, B6_y, B6_z, x_6, y_6, z_6
          real Node6_x, Node6_y, Node6_z, Node6_rel_pos
          real A6_diam, A6_radius, A6_length, MIN_A6_length, MAX_A6_length
          real A6_elevation, A6_azim, A6_phyllo
          real A6_elevation_2, A6_azim_2

          pi = 2.*acos(0.)
          CAM = 1
          CAMOX = 0.             ! (cm) Camera position
          CAMOY = 6000.                   ! (cm) Camera position
          CAMOZ = 1500.          ! (cm) Camera position
          CAMVX = 0.             ! (cm) Camera position
          CAMVY = 0.             ! (cm) Camera position
          CAMVZ = 1500.                   ! (cm) Camera position
c
c         Open the PovRay file Sitka.pov ****************************************************
          open(1,file="Sitka.pov")
          write(1,*) '#declare   CAM =', float(CAM), ';'
```

```
      write(1,*) '#declare XVCAM =', CAMVX, ';'
      write(1,*) '#declare YVCAM =', CAMVY, ';'
      write(1,*) '#declare ZVCAM =', CAMVZ, ';'
      write(1,*) '#declare XOCAM =', CAMOX, ';'
      write(1,*) '#declare YOCAM =', CAMOY, ';'
      write(1,*) '#declare ZOCAM =', CAMOZ, ';'
      write(1,*) '#declare RAPRAYON =', 0., ';'
      write(1,*) '#include "couleur.inc"'
      write(1,*) '#include "ciel.inc"'
      write(1,*) '#include "camera.inc"'
      write(1,*) '#include "feuille.inc"'
      write(1,*) '#include "cylindre.inc"'
      write(1,*) '#include "sol.inc"'
      write(1,*) 'object{ECHELLEZ scale < 1., 1., 1. >',
      & ' texture { ECHELLEtexture1 } }'
      write(1,*) 'object{ECHELLEY scale < 1., 1., 1. >',
      & ' texture { ECHELLEtexture1 } }'
      write(1,*) 'object{ECHELLEX scale < 1., 1., 1. >',
      & ' texture { ECHELLEtexture2 } }'
c     Open the PovRay file Sitka.pov ****************************************************

c     Control screen -------------------------------------------------------------------------------------------------
      write(*,*)'(1) Single tree'
      write(*,*)'(2) Plot'
      read(*,*) Choice(1)
            if (Choice(1)==1) then
            Number_A1=1
            else
            write(*,*)
            write(*,*)'Number of trees for a plot'
            read(*,*) Number_A1
            end if
c     Control screen -------------------------------------------------------------------------------------------------

c     Read empirical relationships in Sitka.dat -------------------------------------------------------------------
      open(2,file="Sitka.dat")
      read(2,*) a(1), b(1)        ! A1_length = f(A1_dbh) y=ax+b
      read(2,*) a(2), b(2)        ! relative position of the 1st alive whorl = f(A1_length) y=ax+b
      read(2,*) a(3), b(3)        ! A1_number_whorl = f(A1_length) y=ax+b
      read(2,*) a(4), b(4)        ! Crown_number_whorl = f(A1_length) y=ax+b
      read(2,*) a(5), b(5)        ! Inter_whorl_length/Crown_length = f(whorl_rank) (metre) y=ax+b
      read(2,*) c(5), d(5)        ! Inter_whorl_length/Crown_length = f(whorl_rank) (metre) y=ax+b
      read(2,*) e(5), f(5)        ! Inter_whorl_length/Crown_length = f(whorl_rank) (metre) y=ax+b
      read(2,*) a(6), b(6)        ! Whorl_number_A2 = f(whorl_relative_position) average SD
      read(2,*) a(7), b(7)        ! MAX A2_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(8), b(8)        ! MIN A2_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(9), b(9)        ! MAX A2_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(10), b(10)      ! MIN A2_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(11), b(11)      ! A2_diam = f(A2_lenght) (metre) crown level y=ax^b
      read(2,*) a(12), b(12)      ! A2_length = f(A2_diam) (metre) crown level y=ax^b
      read(2,*) a(13), b(13)      ! A2_insertion angle Average, SD
      read(2,*) a(14), b(14)      ! A2_number_nodes = f(A2_length) y=ax+b
      read(2,*) a(15), b(15)      ! MAX A3_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(16), b(16)      ! MIN A3_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(17), b(17)      ! MAX A3_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(18), b(18)      ! MIN A3_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(19), b(19)      ! A3_diam = f(A3_lenght) (metre) crown level y=ax^b
      read(2,*) a(20), b(20)      ! A3_length = f(A3_diam) (metre) crown level y=ax^b
```

```
      read(2,*) a(21), b(21)      ! A3_insertion angle Average, SD
      read(2,*) a(22), b(22)      ! A3_number_nodes = f(A3_length) y=ax+b
      read(2,*) a(23), b(23)      ! MAX A4_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(24), b(24)      ! MIN A4_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(25), b(25)      ! MAX A4_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(26), b(26)      ! MIN A4_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(27), b(27)      ! A4_diam = f(A4_lenght) (metre) crown level y=ax^b
      read(2,*) a(28), b(28)      ! A4_length = f(A4_diam) (metre) crown level y=ax^b
      read(2,*) a(29), b(29)      ! A4_insertion angle Average, SD
      read(2,*) a(30), b(30)      ! A4_number_nodes = f(A4_length) y=ax+b
      read(2,*) a(31), b(31)      ! MAX A5_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(32), b(32)      ! MIN A5_diam = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(33), b(33)      ! MAX A5_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(34), b(34)      ! MIN A5_length = f(1-Whorl_relative_position) crown level y=ax^b
      read(2,*) a(35), b(35)      ! A5_diam = f(A5_lenght) (metre) crown level y=ax^b
      read(2,*) a(36), b(36)      ! A5_length = f(A5_diam) (metre) crown level y=ax^b
      read(2,*) a(37), b(37)      ! A5_insertion angle Average, SD
      read(2,*) a(38), b(38)      ! A5_number_nodes = f(A5_length) y=ax+b
      read(2,*)
            do A1=1,Number_A1
            read(2,*) A1_dbh(A1), A1_x(A1), A1_y(A1), A1_z(A1)
            end do
      close(3)
      close(2)
c     Read empirical relationships in Sitka.dat -----------------------------------------------------------------------

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP A (Tree level)

      do A1=1,Number_A1
      A1_length(A1)=a(1)*A1_dbh(A1)+b(1)
      A1_radius(A1)=((A1_dbh(A1)/2.)*A1_length(A1))/
      &(A1_length(A1)-1.3)

c     Write the POV-Ray file: Trunk description = Cone ***************************************
      write(1,10) A1_length(A1)*100., A1_radius(A1)*100.,
      A1_radius(A1)*100., 0., -90., 0.,
      A1_x(A1)*100., A1_y(A1)*100., A1_z(A1)*100.
      format('object{TRUNK scale<',f8.3,',',f8.3,',',f8.3,'> ',
      'rotate <',f8.3,',',f8.3,',',f8.3,'> ',
      'translate <',f8.3,',',f8.3,',',f8.3,'> ',
      'texture{ TRUNKtexture } }')
c     Write the POV-Ray file: Trunk description = Cone ***************************************

c     Control screan ---------------------------------------------------------------------------------------------------
      write(*,*) ' Computation of the tree # :', A1
c     Control screan ---------------------------------------------------------------------------------------------------

      A1_number_whorl=a(3)*A1_length(A1)+b(3)
      Crown_number_whorl=a(4)*A1_length(A1)+b(4)
      Whorl_x=A1_x(A1)
      Whorl_y=A1_y(A1)
      Whorl_z=A1_z(A1)+(A1_length(A1)*(a(2)*A1_length(A1)+b(2)))
      Crown_z=Whorl_z
      A1_cum_iwhorl_length=0.
      do Whorl=1,Crown_number_whorl
      A1_iwhorl_length=((a(5)*(float(Whorl)/float(Crown_number_whorl))
      &+b(5))*(A1_length(A1)-Crown_Z))
      A1_cum_iwhorl_length=A1_cum_iwhorl_length+A1_iwhorl_length
```

```
      end do
      Correction1=(A1_length(A1)-Crown_Z)/A1_cum_iwhorl_length

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP B (Whorl level)

      do Whorl=1, Crown_number_whorl
      Whorl_number_A2=tirage1(a(6),b(6))
      A2_azim=tirage1(180.,180.)
      A2_phyllo=360./Whorl_number_A2

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>  LOOP C (A2 level)

      do A2=1, Whorl_number_A2
      MAX_A2_length=a(9)*
      &((1.-((Whorl_z-Crown_z)/(A1_length(A1)-Crown_z)))**b(9))
      MIN_A2_length=a(10)*
      &((1.-((Whorl_Z-Crown_z)/(A1_length(A1)-Crown_z)))**b(10))
      A2_length=tirage1(((MAX_A2_length-MIN_A2_length)/2.)+MIN_A2_length,
      &(MAX_A2_length-MIN_A2_length)/2.)
      A2_radius=(a(11)*(A2_length**b(11)))/2.
      A2_elevation=90.-tirage1(a(13),b(13))

c     Write the POV-Ray file: A2 description = Cone ****************************************
      write(1,11) A2_length*100., A2_radius*100., A2_radius*100.,
      & 0., -A2_elevation, A2_azim,
      &Whorl_x*100., Whorl_y*100., Whorl_z*100.
      format('object{Axis2 scale<',f8.3,',',f8.3,',',f8.3,'> ',
      & 'rotate <',f9.2,',',f9.2,',',f9.2,'> ',
      & 'translate <',f9.2,',',f9.2,',',f9.2,'> ',
      & 'texture{ AXIS2texture } }')
c     Write the POV-Ray file: A2 description = Cone ****************************************

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP D (Node level on A2)

      A2_number_nodes=a(14)*A2_length+b(14)
      Node_x=0.
      Node_y=0.
      Node_z=(A2_length/(float(A2_number_nodes)+1.))
      do Node_A2=1, A2_number_nodes

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A2)

      Node5_x=0.
      Node5_y=0.
      Node5_z=Node_z-(A2_length/(float(A2_number_nodes)+1.))+0.01
      A6_elevation=30.
      A6_azim=tirage1(180.,180.)
      A6_phyllo=tirage1(45., 0.)
      do Node_A5=1, 50000
      if(Node5_z<=Node_z-0.01) then
      A6_length=tirage1(0.020, 0.0036)+
      (((A2_length-Node5_z)/(A2_length/A2_radius))/
      tan(A6_elevation*pi/180.))

      A5_x = Node5_x
```

```
A5_y = Node5_y
A5_z = Node5_z
B5_x = A6_length*sin(A6_elevation*pi/180.)
B5_y = 0.
B5_z = Node5_z + A6_length*cos(A6_elevation*pi/180.)
x_5 = B5_x
y_5 = B5_y
z_5 = B5_z
B5_x = x_5*cos(A6_azim*pi/180.)+y_5*sin(A6_azim*pi/180.)
B5_y =-x_5*sin(A6_azim*pi/180.)+y_5*cos(A6_azim*pi/180.)
B5_z = z_5
x_5 = B5_x
y_5 = B5_y
z_5 = B5_z
B5_x = x_5*cos((90.-A2_elevation)*pi/180.)-
z_5*sin((90.-A2_elevation)*pi/180.)
B5_y = y_5
B5_z = x_5*sin((90.-A2_elevation)*pi/180.)+
z_5*cos((90.-A2_elevation)*pi/180.)
x_5 = A5_x
y_5 = A5_y
z_5 = A5_z
A5_x = x_5*cos((90.-A2_elevation)*pi/180.)-
z_5*sin((90.-A2_elevation)*pi/180.)
A5_y = y_5
A5_z = x_5*sin((90.-A2_elevation)*pi/180.)+
z_5*cos((90.-A2_elevation)*pi/180.)
x_5 = B5_x
y_5 = B5_y
z_5 = B5_z
B5_x = x_5*cos((180.-A2_azim)*pi/180.)+
y_5*sin((180.-A2_azim)*pi/180.)
B5_y =-x_5*sin((180.-A2_azim)*pi/180.)+
y_5*cos((180.-A2_azim)*pi/180.)
B5_z = z_5
x_5 = A5_x
y_5 = A5_y
z_5 = A5_z
A5_x = x_5*cos((180.-A2_azim)*pi/180.)+
y_5*sin((180.-A2_azim)*pi/180.)
A5_y =-x_5*sin((180.-A2_azim)*pi/180.)+
y_5*cos((180.-A2_azim)*pi/180.)
A5_z = z_5
A6_azim_2=(atan((B5_y-A5_y+1.e-8)/(B5_x-A5_x+1.e-8)))*180./pi
if ((B5_x-A5_x).lt.0.) A6_azim_2=A6_azim_2+180.
A6_elevation_2=(asin((B5_z-A5_z)/A6_length))*180./pi
A5_x = A5_x + Whorl_x
A5_y = A5_y + Whorl_y
A5_z = A5_z + Whorl_z
```

```
c       Write the POV-Ray file: A3 description = Cone ****************************************
        write(1,17) A6_length*100, 0.125, 0.125,
```

```
      0., -A6_elevation_2, A6_azim_2,
      A5_x*100., A5_y*100., A5_z*100.
c     Write the POV-Ray file: A3 description = Cone ******************************************

      A6_azim=amod(A6_azim+A6_phyllo,360.)
      Node5_z=Node5_z+0.001
      end if
      end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A2)
c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP E (A3 level)

      A3_azim=-90.
      A3_phyllo=0.
      do A3=1, 2
      Node2_rel_pos=Node_z/A2_length
      A3_length=0.471*((1-Node2_rel_pos)**0.3116)
      A3_elevation=tirage1(a(21), b(21))

c     Write the POV-Ray file: A3 description = Cone ******************************************
      write(1,12) A3_length*100, 0.5, 0.5,
      0., -A3_elevation, A3_azim,
      A_x*100., A_y*100., A_z*100.
      format('object{Axis3 scale<',f8.3,',',f8.3,',',f8.3,'> ',
      'rotate <',f9.2,',',f9.2,',',f9.2,'> ',
      'translate <',f9.2,',',f9.2,',',f9.2,'> ',
      'texture{ AXIS3texture } }')
c     Write the POV-Ray file: A3 description = Cone ******************************************

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP F (Node level on A3)

      A3_number_nodes=6.24*A3_length+0.24    Node3_x=0.
      Node3_y=0.
      Node3_z=(A3_length/(float(A3_number_nodes)+1.))
      do Node_A3=1, A3_number_nodes

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A3)

      Node5_x=0.
      Node5_y=0.
      Node5_z=Node3_z-(A3_length/(float(A3_number_nodes)+1.))+0.01
      A6_elevation=45.
      A6_azim=tirage1(180.,180.)
      A6_phyllo=tirage1(45., 0.)
      do Node_A5=1, 500
      if(Node5_z<=Node3_z-0.01) then
      A6_length=tirage1(0.020, 0.0036)+
      (((A3_length-Node5_z)/(A3_length/A3_radius))/
      tan(A6_elevation*pi/180.))

c     Write the POV-Ray file: A3 description = Cone ******************************************
      write(1,17) A6_length*100, 0.125, 0.125,
      0., -A6_elevation_2, A6_azim_2,
```

```
        A5_x*100., A5_y*100., A5_z*100.
c       Write the POV-Ray file: A3 description = Cone *****************************************

        A6_azim=amod(A6_azim+A6_phyllo,360.)
        Node5_z=Node5_z+0.001
        end if
        end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A3)
c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP G (A4 level)

        A4_azim=-90.
        A4_phyllo=0.
        do A4=1, 2
        Node3_rel_pos=Node3_z/A3_length
        A4_length=0.213*((1-Node3_rel_pos)**0.202)
        A4_elevation=tirage1(a(29), b(29))

c       Write the POV-Ray file: A3 description = Cone *****************************************
        write(1,15) A4_length*100, 0.25, 0.25,
        0., -A4_elevation, A4_azim,
        A3_x*100., A3_y*100., A3_z*100.
        format('object{Axis4 scale<',f8.3,',',f8.3,',',f8.3,'> ',
        'rotate <',f9.2,',',f9.2,',',f9.2,'> ',
        'translate <',f9.2,',',f9.2,',',f9.2,'> ',
        'texture{ AXIS4texture } }')
c       Write the POV-Ray file: A3 description = Cone *****************************************

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP H (Node level on A4)

        A4_number_nodes=(6.097*A4_length-0.517)+1
        Node4_x=0.
        Node4_y=0.
        Node4_z=(A4_length/(float(A4_number_nodes)+1.))
        do Node_A4=1, A4_number_nodes

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP I (A5 level)
c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A4)

        Node5_x=0.
        Node5_y=0.
        Node5_z=Node4_z-(A4_length/(float(A4_number_nodes)+1.))+0.01
        A6_elevation=45.
        A6_azim=tirage1(180.,180.)
        A6_phyllo=tirage1(45., 0.)

        do Node_A5=1, 500
        if(Node5_z<=Node4_z-0.01) then
        A6_length=tirage1(0.020, 0.0036)+
        (((A4_length-Node5_z)/(A4_length/A4_radius))/
        tan(A6_elevation*pi/180.))

c       Write the POV-Ray file: A3 description = Cone *****************************************
```

```
        write(1,17) A6_length*100, 0.125, 0.125,
        0., -A6_elevation_2, A6_azim_2,
        A5_x*100., A5_y*100., A5_z*100.
c       Write the POV-Ray file: A3 description = Cone ******************************************

        A6_azim=amod(A6_azim+A6_phyllo,360.)
        Node5_z=Node5_z+0.001
        end if
        end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A4)

        A5_azim=-90.
        A5_phyllo=0.
        do A5=1, 2
        Node4_rel_pos=Node4_z/A4_length
        A5_length=0.111*((1-Node4_rel_pos)**0.196)
        A5_elevation=tirage1(a(37), b(37))

c       Write the POV-Ray file: A3 description = Cone ******************************************
        write(1,16) A5_length*100, 0.125, 0.125,
        0., -A5_elevation, A5_azim,
        A4_x*100., A4_y*100., A4_z*100.
        format('object{Axis5 scale<',f8.3,',',f8.3,',',f8.3,'> ',
        'rotate <',f9.2,',',f9.2,',',f9.2,'> ',
        'translate <',f9.2,',',f9.2,',',f9.2,'> ',
        'texture{ AXIS5texture } }')
c       Write the POV-Ray file: A3 description = Cone ******************************************

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A5)

        Node5_x=0.
        Node5_y=0.
        Node5_z=0.01
        A6_elevation=45.
        A6_azim=tirage1(180.,180.)
        A6_phyllo=tirage1(45., 0.)
        do Node_A5=1, 500
        if(Node5_z<=A5_length-0.01) then
        A6_length=tirage1(0.02, 0.0036)+
        (((A5_length-Node5_z)/(A5_length/A5_radius))/
        tan(A6_elevation*pi/180.))

c       Write the POV-Ray file: A3 description = Cone ******************************************
        write(1,17) A6_length*100, 0.125, 0.125,
        0., -A6_elevation_2, A6_azim_2,
        A5_x*100., A5_y*100., A5_z*100.
        format('object{Axis6 scale<',f8.3,',',f8.3,',',f8.3,'> ',
        'rotate <',f9.2,',',f9.2,',',f9.2,'> ',
        'translate <',f9.2,',',f9.2,',',f9.2,'> ',
        'texture{ AXIS6texture } }')
c       Write the POV-Ray file: A3 description = Cone ******************************************
```

```
          A6_azim=amod(A6_azim+A6_phyllo,360.)
          Node5_z=Node5_z+0.001
          end if
          end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A5)

          A5_azim=90.
          end do

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP I (next A5)

          Node4_z=Node4_z+(A4_length/(float(A4_number_nodes)+1.))

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A4)

          if (Node_A4==A4_number_nodes) then
          Node5_x=0.
          Node5_y=0.
          Node5_z=Node4_z-(A4_length/(float(A4_number_nodes)+1.))+0.01
          A6_elevation=45.
          A6_azim=tirage1(180.,180.)
          A6_phyllo=tirage1(45., 0.)
          do Node_A5=1, 500
          if(Node5_z<=Node4_z-0.01) then
          A6_length=tirage1(0.020, 0.0036)+
          (((A4_length-Node5_z)/(A4_length/A4_radius))/
          tan(A6_elevation*pi/180.))


c         Write the POV-Ray file: A3 description = Cone ******************************************
          write(1,17) A6_length*100, 0.125, 0.125,
          0., -A6_elevation_2, A6_azim_2,
          A5_x*100., A5_y*100., A5_z*100.
c         Write the POV-Ray file: A3 description = Cone ******************************************

          A6_azim=amod(A6_azim+A6_phyllo,360.)
          Node5_z=Node5_z+0.001
          end if
          end do
          end if

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A4)

          end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP H (Next Node on A4)

          A4_azim=90.
          end do

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP G (next A4)

          Node3_z=Node3_z+(A3_length/(float(A3_number_nodes)+1.))

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A3)
```

```
          if (Node_A3==A3_number_nodes) then
          Node5_x=0.
          Node5_y=0.
          Node5_z=Node3_z-(A3_length/(float(A3_number_nodes)+1.))+0.01
          A6_elevation=45.
          A6_azim=tirage1(180.,180.)
          A6_phyllo=tirage1(45., 0.)
          do Node_A5=1, 500
          if(Node5_z<=Node3_z-0.01) then
          A6_length=tirage1(0.020, 0.0036)+
          (((A3_length-Node5_z)/(A3_length/A3_radius))/
          tan(A6_elevation*pi/180.))
```

```
c         Write the POV-Ray file: A3 description = Cone ******************************************
          write(1,17) A6_length*100, 0.125, 0.125,
          0., -A6_elevation_2, A6_azim_2,
          A5_x*100., A5_y*100., A5_z*100.
c         Write the POV-Ray file: A3 description = Cone ******************************************

          A6_azim=amod(A6_azim+A6_phyllo,360.)
          Node5_z=Node5_z+0.001
          end if
          end do
          end if

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A3)

          end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP F (Next Node on A3)

          A3_azim=90.
          end do

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP E (next A3)

          Node_z=Node_z+(A2_length/(float(A2_number_nodes)+1.))

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> LOOP J (Needles level on A2)

          if (Node_A2==A2_number_nodes) then
          Node5_x=0.
          Node5_y=0.
          Node5_z=Node_z-(A2_length/(float(A2_number_nodes)+1.))+0.01
          A6_elevation=30.
          A6_azim=tirage1(180.,180.)
          A6_phyllo=tirage1(45., 0.)
          do Node_A5=1, 50000
          if(Node5_z<=Node_z-0.01) then
          A6_length=tirage1(0.020, 0.0036)+
          (((A2_length-Node5_z)/(A2_length/A2_radius))/
          tan(A6_elevation*pi/180.))
```

```
c          Write the POV-Ray file: A3 description = Cone *****************************************
           write(1,17) A6_length*100, 0.125, 0.125,
           0., -A6_elevation_2, A6_azim_2,
           A5_x*100., A5_y*100., A5_z*100.
c          Write the POV-Ray file: A3 description = Cone *****************************************

           A6_azim=amod(A6_azim+A6_phyllo,360.)
           Node5_z=Node5_z+0.001
           end if
           end do
           end if

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP J (Next Needle on A2)

           end do

c>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> END LOOP D (Next Node on A2)

           A2_azim=amod(A2_azim+A2_phyllo,360.)
           end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP C (next A2)

           Whorl_z=Whorl_z+(((a(5)*(float(Whorl)/float(Crown_number_whorl))
           +b(5))*(A1_length(A1)-Crown_Z)))*Correction1
           end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP B (next whorl)

           end do

c<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< END LOOP A (next Tree)

           close(1)
           close(4)
           stop
           end

           real function tirage1 (average, sdt_dev)
           do i=1, 1000
           CALL RANDOM_NUMBER (harvest)
           end do
           tirage1=average+(((2.*harvest)-1.)*sdt_dev)
           end function
```