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Structure Model for Crown Architecture

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EXECUTIVE SUMMARY

It is the variability of wood properties within (and between) trees that ultimately governs suitability for end use and product performance. Within Objective 2, a modelling framework is being developed to simulate the formation of wood within a growing tree. The aim is to elucidate the processes influencing the variable properties of wood formed at different locations and times within a tree. A key component of the modelling framework is an architectural (spatial) description of the stem and its branches, as this forms the skeleton for subsequent wood formation. This architectural skeleton establishes the structure on which all the various processes of growth are carried out, and therefore plays an important role in the dynamics of those processes and hence the properties of the wood formed at any given point within a tree.

This report describes a module constructed to create a three-dimensional architectural description of a growing tree as it develops through time. The module is linked into the larger modelling framework which will progressively elaborate various relevant processes, allowing simulation of wood formation on a growing tree. The architectural module is therefore a component of a much larger modelling system that is under long-term development.

The architectural module uses Cabala, a stand level process model for tree growth, and BLOSSIM, a branch growth model, to provide branch locations within annual shoots and clusters on the stem. A simple relationship is used to estimate branch length from branch diameter. These models are used in combination to produce a spatially explicit three-dimensional skeleton describing the primary growth (elongation) of the stem and first order branches at annual time steps. An additional simple relationship is used to estimate the total mass of foliage carried by each branch at each time step.

The newly developed architectural module provides a spatial skeleton to be used by other modules within the modelling framework to carry out simulation of wood formation. Through the functionality of Cabala and BLOSSIM, it will be possible to simulate tree architectures for radiata pine that might reflect to some degree influences from differing sites, environmental factors, silvicultural regimes and genetics.

INTRODUCTION

The model of wood formation under development within Objective 2 requires the architectural structure of a growing tree. In this case tree architecture is defined as a spatially explicit description of the stem and at least the first order branches. Wood formation is carried out in the cambial region. The properties of the wood formed are determined by local levels of a number of factors such as: assimilate supply (in turn governed by water supply to foliage); mechanical stresses and strains; and growth hormones. Given that the overall goal of the model is to help understand variability in wood products, it is essential that the model incorporate the architectural structure of the tree because it establishes the spatial framework within which wood formation occurs. The spatial arrangement of sources and sinks for processes to be modelled such as water and assimilate transport will provide the basis for variation in the properties of the wood formed by the cambium at any given point on the surface of the tree stem. In addition the branches themselves induce significant local variation in wood properties within the stem, most obviously in the form of knots and surrounding grain deviation.

Tree architecture can be represented at different levels of detail. At a low level of detail the entire crown might be represented as a single component. This would simplify the model but would not allow for meaningful variation in growth processes except for positions on the stem well below the crown. At a high level of detail it could include all orders of branching and individual leaves (needles). This would be a highly complex model, more able to support realistic local variation in growth processes, but with onerous computational requirements. Significantly, such a complex model of tree architecture is not currently available to us and it would require a huge effort in data collection and model development to produce one.

The decision made was to utilise existing models to create a crown architecture component that represents the stem and the first order of branching. An architectural model at this level of detail provides an adequate basis for simulating the required processes such as water and carbon transport, and mechanical loads, and can be constructed with a reasonable amount of effort.

METHODS

A model of branch development (BLOSSIM) has been developed for New Zealand-grown radiata pine (Grace *et al*. 1998, 1999). The model predicts branch location on the stem in terms of: vertical position within an annual shoot, and azimuthal angle according to phylotaxis (Pont 2001); it also predicts branch annual diameter growth, governed by factors such as stocking and tree DBH. The model has been parameterised for the major NZ growth regions and for unimproved, multi-nodal and uni-nodal genetic groups. In order to simulate the growth of all branches on a tree, BLOSSIM requires a stand- or tree-level growth model to provide annual estimates of tree diameter and height.

The growth model Cabala (Battaglia *et al*. 2004) uses inputs such as rainfall, temperature and tree spacing to estimate variables such as biomass production, carbon sequestration, nitrogen content and canopy height of trees in plantations and forests. The model is attractive because it uses tree physiological parameters, site factors and environmental conditions to predict tree growth. The model also predicts tree architectural variables such as mean height, diameter, branch length, green height and crown length, but it does so only for a nominal 'mean tree'. This level of architectural description is not sufficient for our requirements.

The approach adopted is to use Cabala to provide height and diameter growth of a tree, and BLOSSIM to estimate the location and growth of branches on that tree. These two models allow an architectural model of a single tree to be created, in terms of annual growth of the main stem and first order branches. The architectural model is a kind of 'stick' model of the tree, describing primary (elongation) growth. Another component in the modelling system is responsible for secondary (diameter) growth on the architectural framework.

Cabala is run using a set of parameters provided for radiata pine, and an output file containing a comprehensive set of growth outputs is saved as an Excel spreadsheet. The spreadsheet is saved as a tab delimited text file with values at monthly time-steps. This text file is the input to the main python script cabalatree.py which extracts required information from the Cabala output and creates the architectural model of a single tree. The fields extracted from the Cabala file are: 'Stand age', 'Diam (cm)', 'Ht (m)', 'Stocking/ha', 'Cumulative Thin Vol m³/ha. The 'Ht' and 'Diam' fields are used to represent the total height and DBH of the mean tree for the stand.

The branch model has been implemented in the python module bdmodel.py. As a first step the branch model is initialised with a fixed seed for its internal stochastic functions, and Central North Island region and multi-nodal genetics are specified.

The text file is read sequentially, and at each annual time-step a new annual shoot is created for the main stem. In terms of the architectural output, this is simply a vertical line segment representing the length of the shoot. For each new annual shoot the branch model is used to create one or more branch clusters (whorls), each containing one or more branches, each with a distinct point of origin along the stem and in terms of azimuth (angle around the stem). Next the growth of all pre-existing and new branches is estimated in terms of status (alive or dead), diameter, angle (from horizontal) and length.

In fact the BLOSSIM model does not incorporate branch length. As length is a critical aspect for an architectural model, this functionality was added using a relationship between branch diameter and length derived by Fernandez and Norero (2006) from 2127 branches from age 15 radiata pine trees on two sites in Chile, with and without silvicultural treatment (pruning and thinning). A single linear relationship was found to be sufficient for all branches from the different sites and management regimes. As such this relationship was considered adequate for initial use in the architectural modelling.

A key part of the overall tree modelling process is to accumulate individual sink demands such as water uptake, and to partition global assimilate production. In the current implementation it was decided to use the amount of foliage carried by each branch as a useful value for estimating factors such as demand for water, masses for mechanical load calculations, and partitioning global assimilate production (from Cabala). Foliage mass carried at each age is estimated for every branch from branch basal area increment using a relationship derived by Pont (2001). This aspect is not strictly part of an architectural model, but it was convenient to incorporate this functionality within the architectural model for now.

The architectural model outputs four tab delimited text files, one each for shoot, cluster, branch and annual growth information. The files are named with suffixes added to the name of the input Cabala file. For example for an input file named:

```
NSA_JU06_1.csv
```

The output files are named:

```
NSA_JU06_1_Shoot.txt
NSA_JU06_1_Cluster.txt
NSA_JU06_1_Branch.txt
NSA_JU06_1_Growth.txt
```

The fields in the files are defined here.

Shoot:

Shoot	Shoot number from 1 to A where A is final stand age
TopHeight_m	Height to the top of the shoot
ShootLength_m	Length of the annual shoot
NClusters	Number of branch clusters (whorls) located on the shoot

Cluster:

Cluster	Cluster number from 1 to C where C is number of clusters on the tree.
ClusterHeight	Height in the tree to insertion point of highest branch in the cluster
TreeAgeClusterCreated	Tree age in years when the cluster was formed
NBranches	Number of branches in the cluster

Branch

BranchIdx	Branch number from 1 to B where B is number of branches on the tree
ClusterIdx	Number of the cluster the branch belongs to
BranchOriginHeight_m	Height in the tree to insertion point of the branch

Growth

BranchIdx	Number of the branch
Alive	1 = alive, 0 = dead
Age_y	Tree age at which this branch growth data generated
FoliageMass_kg	total mass of live foliage carried by the branch
LengthIncrement_mm	length increment of the branch
VectorX, VectorY, VectorZ	3 tab delimited values for a vector representing the orientation of this branch length increment

RESULTS

The four text files generated by the tree architecture component are used by the wood formation modelling framework during the simulation of a growing tree.

Figure 1 shows three-dimensional tree architecture generated for a 23-year-old tree. The tree contains 23 annual shoots, 46 branch clusters and a total of 268 living and dead branches. Close examination of larger branches in the middle and lower crown show they follow a progression from increasing to declining length increments with age.

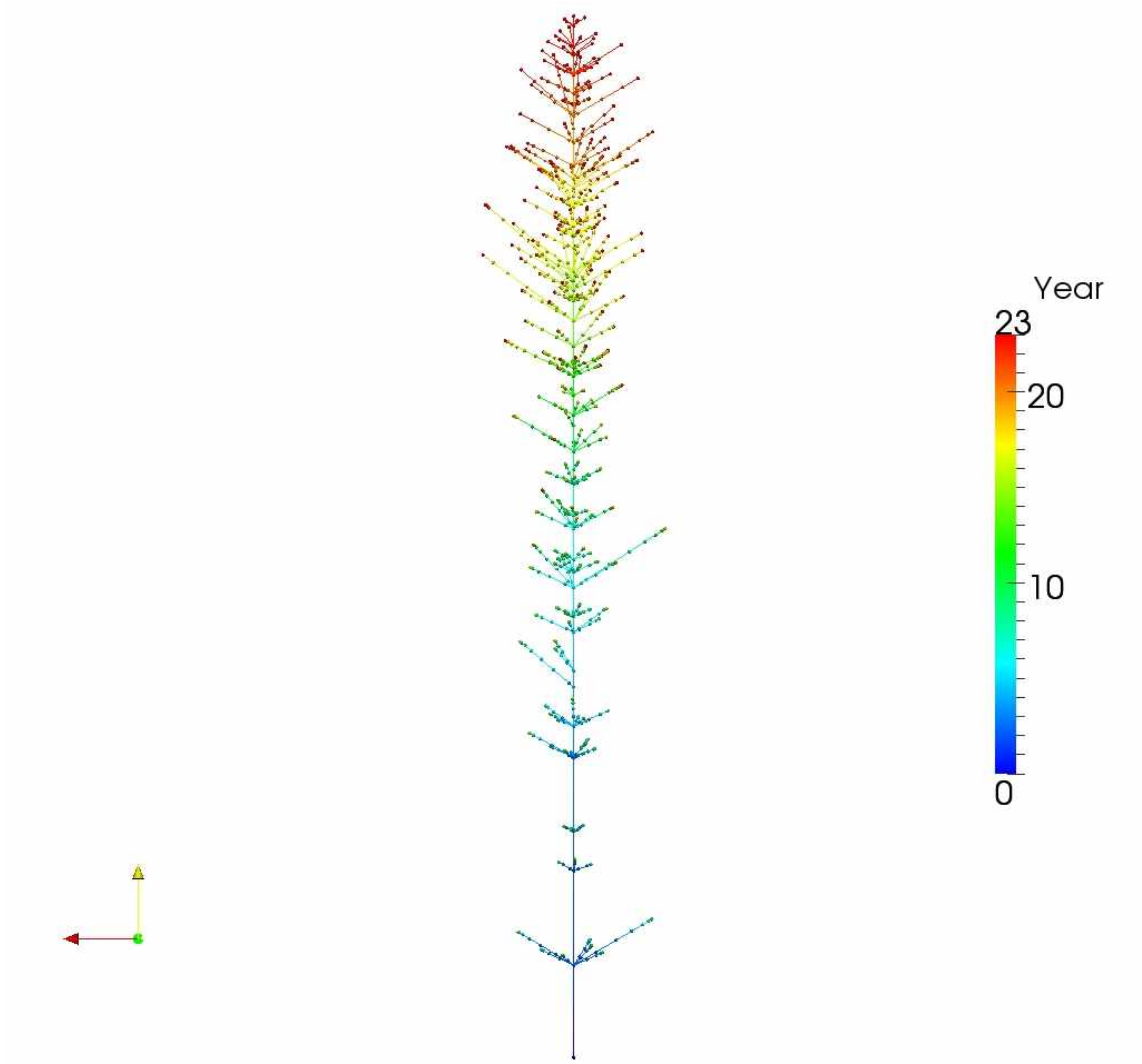

Figure 1. Representation of the three-dimensional architectural framework generated for a single tree at age 23. The central vertical line is the main stem, other lines are branches. A small point is placed at the end of each annual growth increment. Lengths of the stem and branches are to actual scale. Colour is used to indicate the year in which each growth increment occurred.

Figure 2 represents the same tree in Figure 1, but rather than showing stem and branches to actual scale it uses unit lengths to represent each annual growth increment. This shows, in a more compact form, the distribution of different-aged elements within the crown.

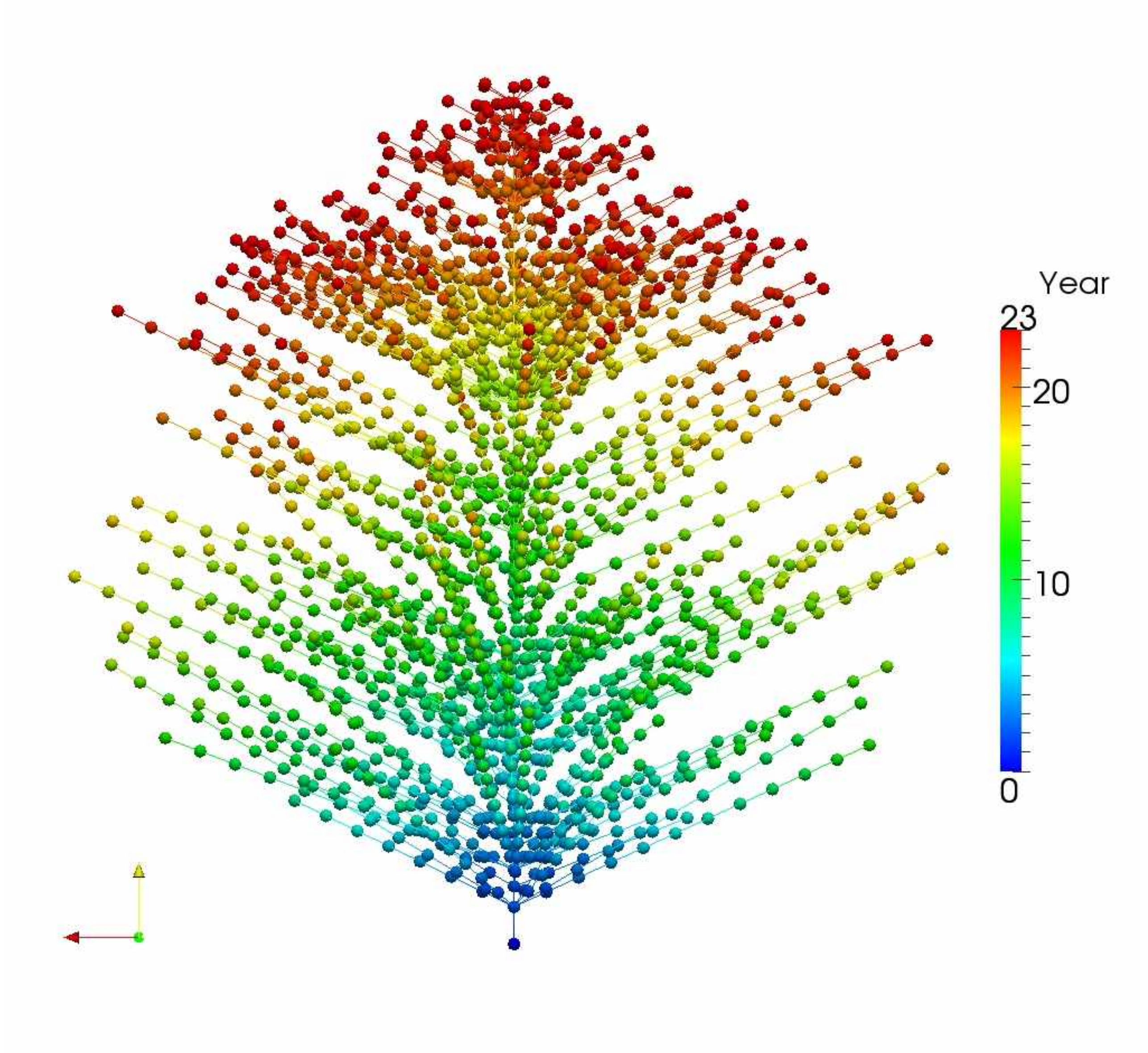

Figure 2. Representation of the three-dimensional architectural framework generated for a single tree at age 23. The central vertical line is the main stem, other lines are branches. A small point is placed at the end of each annual growth increment. Lengths of lines are not to actual scale, but each annual growth increment is a unit length. Branch lengths represent current (or final) ages, most obvious at the top of the crown. Colour is used to indicate the year in which each growth increment occurred.

The tree architecture component has been successfully linked to the wood formation modelling framework and a set of unit tests devised to verify its functionality. Figure 3 shows the shape of a tree at age 4 after diameter growth has been modelled on top of an underlying architectural structure.

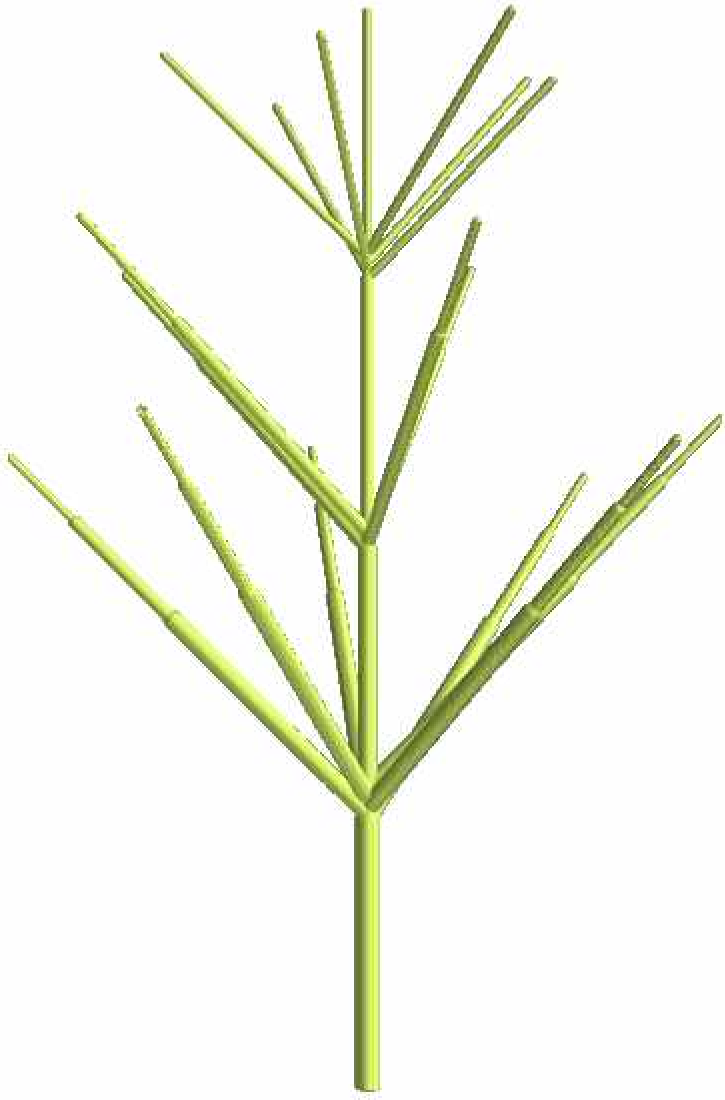

Figure 3. Image of a tree from the modelling framework at age four. An architectural tree model has been used as the basis for simulation of secondary (diameter) growth.

CONCLUSION

A module has been developed to produce an architectural description of a growing tree through time. The architectural model includes the stem and first order branches only, with no higher order branches. The module uses Cabala growth model for stem growth and the BLOSSIM branch model for branch growth. The model represents primary growth, that is, the longitudinal extension of apical meristems at regular time intervals. The time interval used currently is one year, but the Cabala data used as input would allow a time interval as short as one month if desired.

The output of the architectural model also incorporates an estimate of branch foliage mass at each time step. This value can be used for input to transport, allocation and mechanical modules within the framework.

ACKNOWLEDGEMENTS

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