Growing confidence in forestry's future Research Programme

SCION FORESTS ▪ PRODUCTS ▪ INNOVATION

Date: 22/6/2018
Reference: GCFF-TN022

File Note

Large-scale modelling of sugar transport in trees: potential for precision forestry

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Summary: The transport of sugars ("carbon") in trees is an important ecophysiological process. The ability to describe that process is key to understand the growth performance of individual trees and to evaluate the potential margins for productivity increase. Modelling sugar transport is also an essential element of a computer-assisted approach to anticipate the impact of forest management on wood properties and resource quality. With this study, we demonstrate that it is possible to apply deterministic models of sugar transport for practical purposes such as investigating how real trees function thanks to the availability of remote sensing data. Tree stem surfaces were reconstructed from an existing terrestrial LiDAR dataset collected in a commercial Radiata plantation. Hydraulic properties were determined by image analysis of phloem tissue anatomy. Numerical simulations of sugar transport for a real system were performed for the first time.

Introduction

In trees, sugars are produced in the leaves and transported through the phloem. Although essential to plant function, phloem is one of the least understood tissue in plant biology. It is located under the bark and sheathes almost the entire tree surface. Like wood (xylem), phloem is composed of elongated and interconnected cells. The network of those cells constitutes the conduit through which sugar-loaded sap, driven by a pressure gradient, flows. Understanding phloem sap flow is critical to assess the fluxes of carbon between the atmosphere and soils as well as the capacity for carbon sequestration. Sugar transport also dictates what growth rates are achievable and how the carbon is partitioned within the tree, which has an impact on forest productivity and wood quality, respectively. Moreover, phloem plays a role in drought-induced tree mortality.

We intend to demonstrate that, using remote sensing technology and high performance computing, it is possible to apply complex biophysical models to investigate and better understand the physiology of real tree organisms.

To date, most models of sugar flow have focused on the theoretical underpinnings of the transport mechanism in idealised crop plants. As a result, there exists a significant knowledge gap regarding translocation in trees in general and conifers in particular. Addressing that gap is very important because of the predominant use of softwood species in plantation forest world-wide. In New Zealand, 97% of planted trees are conifers. The modelling of sugar transport at the individual tree scale also has potential applications for precision forestry. It can be used to predict the allocation of carbon along the tree stem and link growth to wood quality as a function of the local physical environment in which the tree is grown but also depending on the tree's own traits (e.g. crown structure). Individual variation between and within trees has a major effect on the quality of the wood supply.

A workflow is developed to simulate the theoretical flow of sugars for existing trees. The workflow relies on characterising the geometry and the hydraulic properties of the transport system. Tree stem shape was obtained by processing terrestrial LiDAR data to a reconstruct a numerical model of the tree using

supported by forestgrowers commodity levy

FOREST GROWERS RESEARCH

This programme is also funded by Scion and the Ministry of Business, Innovation and Employment, New Zealand.

computational geometry algorithms. Hydraulic properties were derived from phloem microscopy samples using digital image processing and analysis. To our best knowledge, this is the first time simulations of phloem transport are carried out using Finite Element Analysis on a real 3D tree structure.

Method

Tree surface reconstruction

Twenty Radiata pine trees are represented in a three-dimensional point set measured by multiple terrestrial LiDAR (FARO) scans. The trees are clonal material from Tarawera forest (Hancocks, cpt 84/2). They were subjected to intensive measurement, notably to destructive sampling to describe their internal distribution of wood properties. The LiDAR scene was split into individual point sets (XYZ file) for each tree by manual selection.

The point sets of trees 1, 3, and 4 were processed so as to obtain a triangular surface mesh that can be used for numerical simulations of sap flow. As the first step, the data is clipped (see fig.1):

- near tree base (to remove any elements from the ground)
- in the upper crown part (where point density drops below a user-defined threshold)
- axisymmetrically (around the stem) to preserve only primary branch stubs and remove outliers.

This task was automated using a Python script.

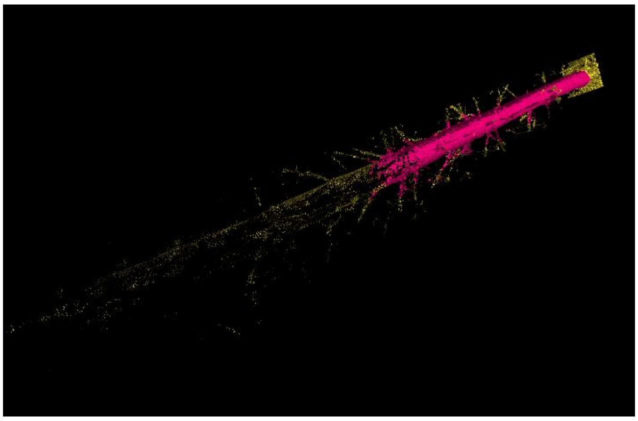

Figure 1: Point set data clipping (tree 3).

In a second step, the data is both simplified and regularised. A single tree can be represented by over a million points which can make some operations computationally expensive. Similarly, the spatial sampling is irregular and some part of tree surface are oversampled while others are ill-defined (e.g. branch shadowing). Using a Poisson disk subsampling procedure (www.meshlab.net), the point set is both simplified and spatially resampled to a user-defined target size (here typically 100,000 to 250,000 points). The difference between the original point set and the resampled one is shown in fig. 2.

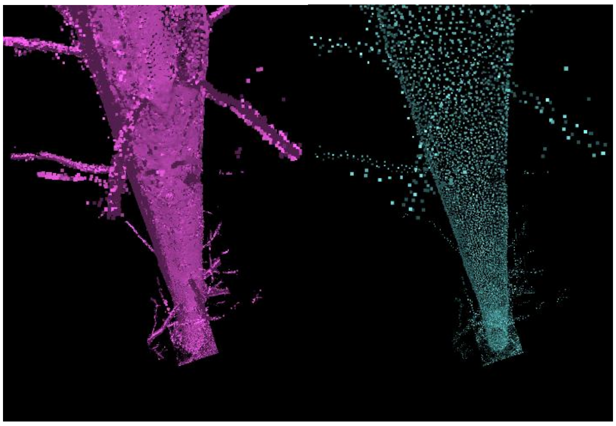

Figure 2: Simplification and regularisation of a LiDAR point set

The third step in processing the point set is to estimate and orient the direction normal to the surface at all points. Several algorithms were tested. The one provided by the Meshlab software was found to be significantly faster than any other options. However, if the task requires automation, a C++ executable using another procedure (see CGAL library, www.cgal.org) is available.

After processing, the point set is used by a Poisson surface reconstruction algorithm (www.cgal.org) to obtain a three-dimensional surface represented by triangular elements (fig. 3). This algorithm is particularly useful in that it is not too sensitive to the presence of holes (regions without points) and it generates triangular elements of sufficient quality for Finite Element Analysis. Finally, the surface is extruded with a finite thickness and converted to a tetrahedral mesh (fig. 4), as required by the phloem transport model.

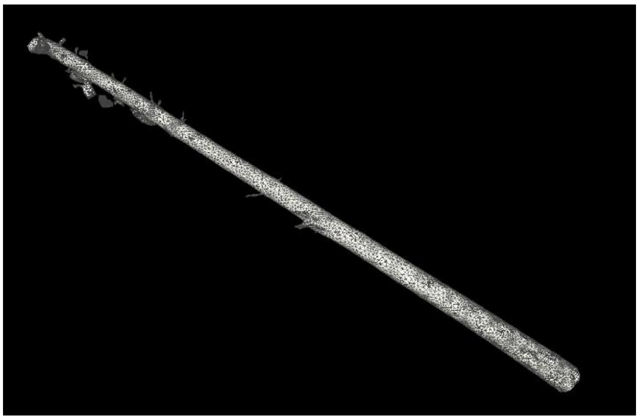

Figure 3: reconstructed tree stem surface

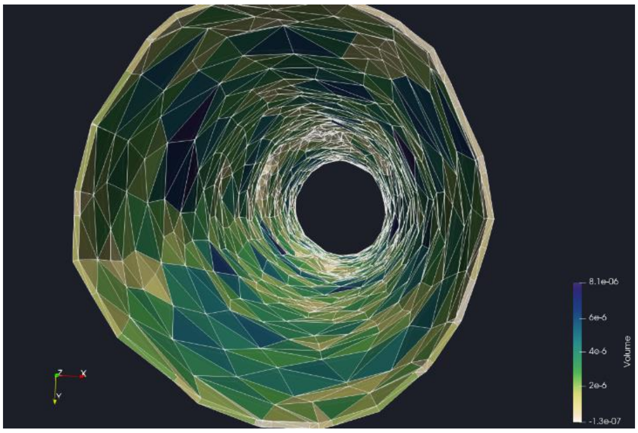

Figure 4: surface mesh extrusion

Hydraulic properties

Phloem sap flow is a type of Darcy flow, which is a pressure-driven flow through a porous medium. The hydraulic conductance of the medium depends on the conductive area, the medium's permeability and the fluid viscosity. In the case of phloem sap, the viscosity exclusively depends on sugar concentration and temperature; it can be determined theoretically and reliably. On the other hand, the conductive area and the permeability must be determined on a case-by-case basis by analysing the phloem tissue of the studied tree.

A phloem sample was collected on three different trees with varied DBH. The selected trees have the same genotype and the same provenance as the trees scanned with terrestrial LiDAR. The samples were extracted using a 2-cm diameter punch and preserved in FAA. It was not always possible to prevent the sample to split on the cambium (in between wood and phloem) despite some modifications done to the sampling technique to avoid this particular issue. Cambium rupture, if it happened, did not preclude the measurement of phloem anatomy but it made it difficult to define the tissue's boundary as it induced cell collapse around the ruptured region. Samples were imaged with fluorescence microscopy. Fig. 5 shows the different zones composing the inner bark of radiata tree.

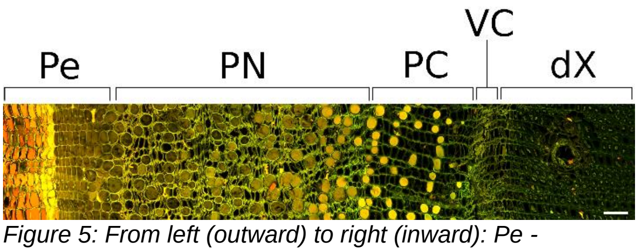

Figure 5: From left (outward) to right (inward): Pe - Periderm, PN - Non-conductive phloem, PC - Conductive Phloem, VC - Vascular Cambium, dX - differentiating Xylem (not conductive). Scale bar is 100 µm.

The phloem is separated in two distinct parts. The outer part is not conducting sap and consists of older sieve cells crushed and dilated axial parenchyma cells. The inside part is conducting sap through the lumen of the sieve cells. Other cells than sieve cells are present in the phloem in smaller numbers. The most common are axial parenchyma cells, which are often filled with polyphenols. Rays (radial parenchyma cells) are also present. They extend from phloem through to xylem and likely play a role moving sugars radially. The thickness of the conductive phloem and the lumen area of individual sieve cells in the conductive phloem were determined by manual image processing (fig. 6). Using a unified theoretical model of transport in tracheary element with porous connections, the hydraulic resistance of each cell was calculated and the permeability for the entire tissue was derived.

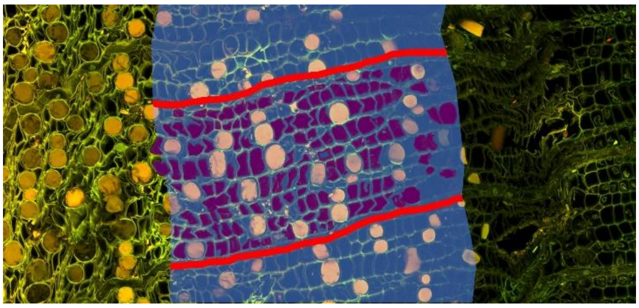
Figure 6: approximated phloem conductive area (light blue) and individual cell lumens (purple). In red, limits of the sampling zone.

The width of the conductive phloem varied from 0.35 to 0.72 mm between the first three samples. The width increased with tree DBH (from 32.8 to 49.7 cm) although not linearly. Permeability varied less, from 8.1 to 13.6 µm^2, and was highest for the tree with the smallest DBH.

Numerical simulations

After combining geometrical and hydraulic data, a special-purpose finite element model of phloem transport was used to predict phloem pressure (fig. 7), sugar concentration and flow rates at every point of a stem section. Those simulations are a first step towards modelling the entire tree stem (large-scale) for several days (long-time). They demonstrate the approach presented in this study is feasible.

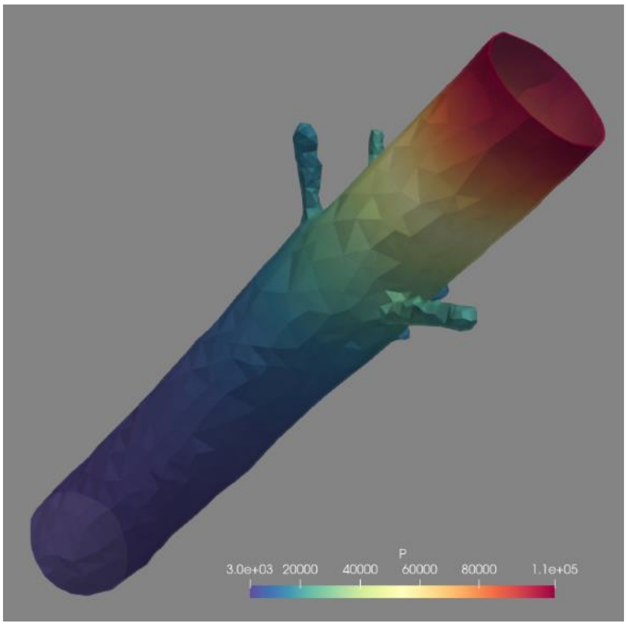

Figure 7: Map of phloem pressure on a stem segment predicted by mathematical modelling.

Next steps

The main aim of this study was to apply a deterministic model of phloem transport to a practical case, i.e. for a real phloem arrangement. While demonstrating the approach is viable, it is the initial phase of this work. It can be developed in several directions:

- To liaise with the FII team at SCION to refine the point set processing workflow and to obtain the LiDAR dataset of an individual tree with higher resolution for the crown and upper stem.
- To continue improving on the 3D phloem transport model and its parameterisation.
- To study the relationship between individual stem shape and carbon partitioning on the stem surface to identify growth patterns.
- To gather more data about phloem anatomy and to evaluate possibilities for semi-automated image processing.
- To assess the vigour and physiological performance of standing trees.

Acknowledgements

"Funding for this research came from the “Growing Confidence in Forestry’s Future” research programme (C04X1306), which is jointly funded by the Ministry of Business Information and Employment (MBIE) and the Forest Growers Levy Trust, with the support of the NZ Forest Owners Association (FOA) and the NZ Farm Forestry Association (FFA)."