Predicting future forest attributes in a world of change

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Welcome note from the Chairperson

Dear Delegate

On behalf of the Scientific and Organising Committees, it gives me great pleasure to welcome you to Stellenbosch and our IUFRO "New Frontiers in Forecasting Forests" (NFFF) conference. We hope that this meeting will indeed showcase the cutting edge ("new frontiers") in forest modelling research generally, and approaches to predicting future forest attributes ("forecasting") in particular.

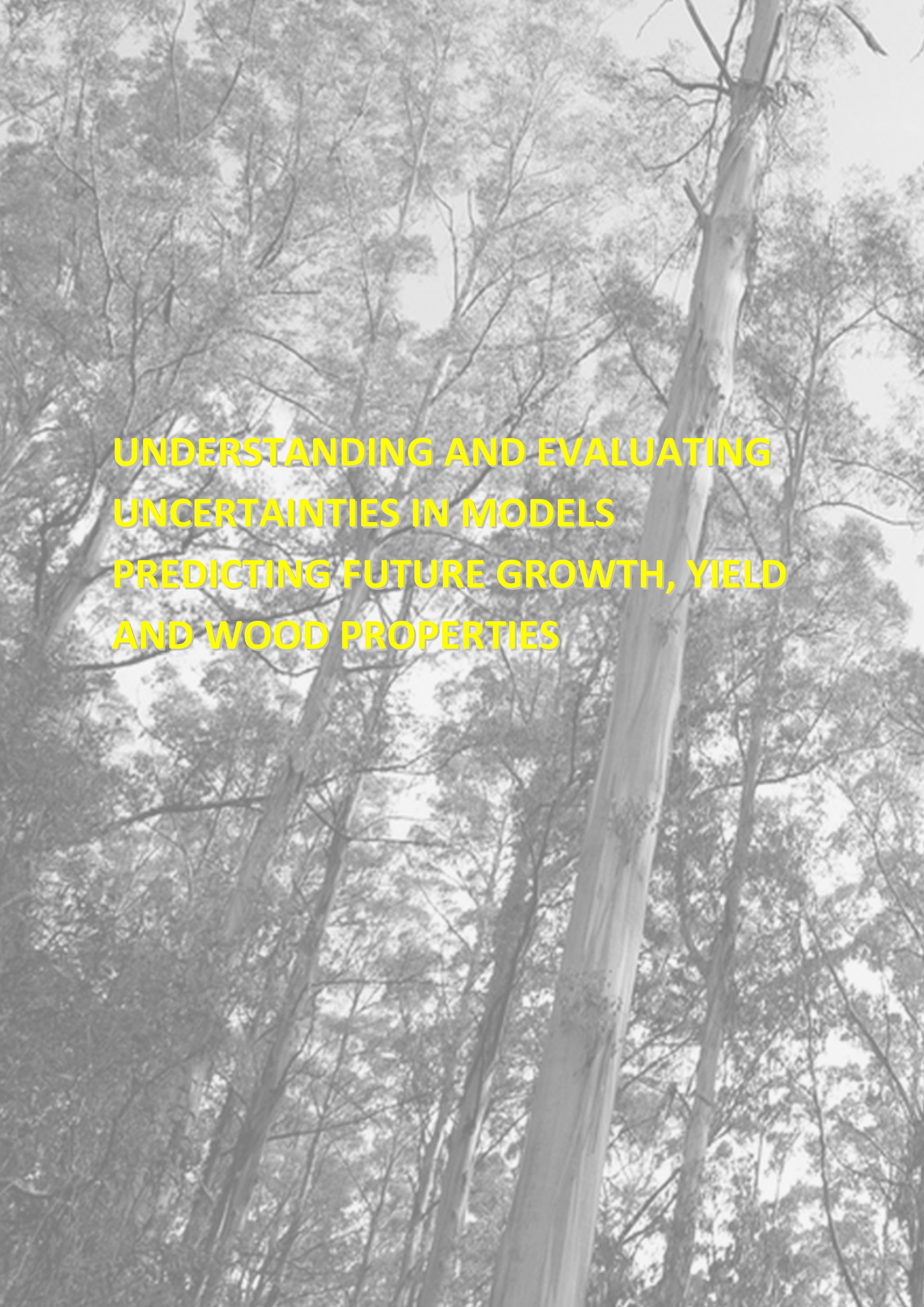
The ability to accurately predict future forest growth and structure, and the yields and quality of diverse products from these forests, is an essential part of forest management. With changes in global climate patterns, rapid genetic gains in commercial forest sectors around the world and the serious risks posed internationally by pests and diseases, forecasting how forests will develop is increasingly challenging. New innovations in statistical modelling techniques, as well as significant advances in process-based modelling approaches are leading, however, to major improvements in modelling success. In the context of challenges facing forestry professionals around the world, this conference brings together scientists, modelers and managers in a focused forum to present and discuss model advancements around four main themes:

- Understanding and evaluating uncertainties in models predicting future growth, yield and wood properties
- The nexus between models of tree growth, wood formation and product properties
- Model application, integration and accessibility for forest management, planning and product development
- The cutting edge in forest measurements and models

When I first began discussions on the idea of this meeting, it became clear that there was real interest from experts around the world in a conference with such a focus. Support from various groups within IUFRO divisions IV and V was immediate, which was a great motivator to press on. Then, the excellent response in papers submitted (65, of which 49 were finally accepted) and registrations (over 80) was the final confirmation. What began as an idea discussed over a cup of coffee has become an exciting reality! It is also particularly pleasing to be able to host this meeting in Stellenbosch on the centennial year of Stellenbosch University, within which our Department of Forest Science finds its home.

We are delighted to make available these proceedings, which include the extended abstracts of all papers presented at the meeting. The peer review process was rigorous and ensured that only the best papers made the "final cut". I am extremely grateful to our Scientific Committee for their invaluable contribution to ensuring that we maintained such a high standard. I look forward enormously to this meeting: opportunities to learn what others are doing, to build new networks and to review old friendships. We hope you will enjoy Stellenbosch and Cape Town and the various events scheduled as part of the meeting!

Dr David Drew, Chairperson of the Organising and Scientific Committees of NFFF 2018



UNDERSTANDING AND EVALUATING UNCERTAINTIES IN MODELS PREDICTING FUTURE GROWTH, YIELD AND WOOD PROPERTIES

KEYNOTE: UNCERTAINTIES IN PREDICTIONS OF GROWTH AND YIELD

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Growth and yield models of varying levels of complexity have been developed to provide forecasts of future stand structure and value. For even-aged stands, growth and yield is typically predicted from stand age, site quality, stand density, and management treatments. Past emphasis has been on estimation of average values; an overall estimate of prediction error at the stand level is seldom provided.

Prediction error increases as projection length increases. Furthermore, past environmental conditions embodied in the data used to estimate model parameters may not apply to the future. Each stand experiences unique environmental influences and disturbances. Consequently, a forest inventory is often conducted at various times during the rotation to adjust for subsequent model projections. Inventory statistics, as well as model predictions, are subject to statistical error. Assessment of prediction error is complex and requires incorporation of error at all stages, including error in field measurements, model parameter estimates, and inventory statistics used to adjust future projections. Partitioning and estimating overall error of the system is needed to determine which parts are most critical and for "optimizing" expenditures allocated to field inventories and model development.

Geospatial information and computing technologies allow the fusion of informatics and statistical modeling. These technologies have greatly increased the efficiency of planning inventories as well as the collection, storage, management, and use of stand-specific inventory data and auxiliary information. Computationally intensive methods for partitioning and estimating variance components of yield forecasts are doable. Refining methods to optimize inventory and model inputs for forest management decision support is practicable and will facilitate obtaining key information at lower cost.

QUANTIFYING MODEL- AND SAMPLING-RELATED UNCERTAINTY IN LARGE-AREA GROWTH PREDICTIONS

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Introduction

Over the last two decades, there has been an increasing demand for large-area predictions at the regional and national levels partly due to international agreements concerning climate change. Uncertainty quantification of large-area predictions is not straightforward for several reasons. Two major sources of uncertainty can be identified: the model and the sampling. Estimating the contribution of each can provide guidelines in the efforts to reduce prediction uncertainty. The aim of this study was to break down the total prediction variance into a model and a sampling componentThis was made possible by using a bootstrap hybrid estimator. Through a variance decomposition approach, the contribution of each sub-model (i.e., growth, mortality and recruitment) to prediction uncertainty was also assessed in order to determine which one contributed most to the variance of large-area growth predictions. We worked with ARTEMIS, a tree-level growth model (Fortin and Langevin, 2012), which was used to generate large-area predictions for the Bas-Saint-Laurent region in Quebec, Canada.

Materials and methods

We worked with the 2009 version of the distance-independent tree-level growth model ARTEMIS (Fortin and Langevin, 2012) in order to generate growth predictions for the administrative region of Bas-Saint-Laurent, which encompasses broadleaved, mixed and coniferous ecotypes. Based on a dataset of 188 plots from Quebec's provincial forest inventory (Figure 1), the framework of the simulations consisted of 100-year growth predictions of basal area based on 10 000 Monte Carlo realizations. These predictions were run by ecotypes excluding disturbances. We also considered a 2◦C temperature increase over the 21st century. First, a reference simulation was carried out in a full stochastic mode. Then, we ran a series of simulations in a partial stochastic fashion, aiming at decomposing the total variance. Using a bootstrap variance estimator proposed by Fortin et al. (2018) made it possible to distinguish the variance that stemmed from the sampling from that of the model.

Results

The sampling showed the greatest contribution to the total variance. This contribution decreased all along the projection length and more sharply during the first half. It mainly explained the decrease in the total variance. The model-related variance represented a smaller proportion of the total variance, with no contribution at all at the beginning of the projection. However, this variance increased along the projection length until it represented almost half the total variance at the end of the projection.

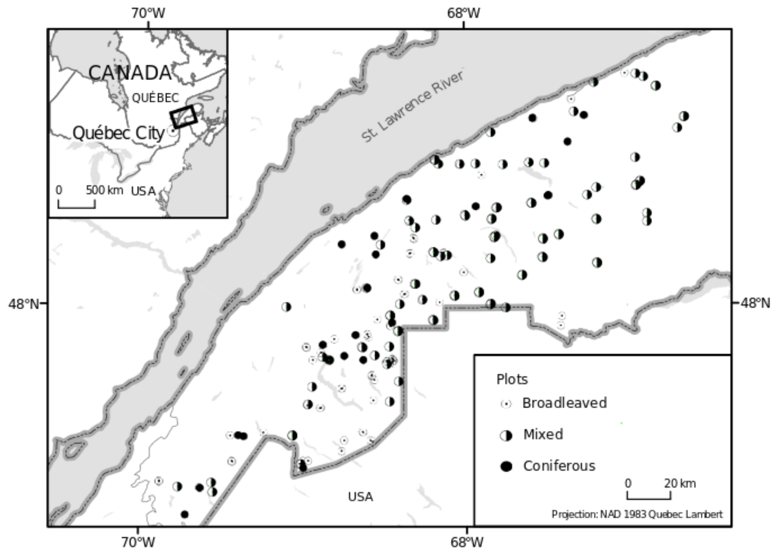

Figure 1: Distribution of the permanent plots that compose the network of Quebec's provincial forest inventory in Bas-Saint-Laurent.

The variance estimates obtained in the partial stochastic predictions revealed that the mortality sub-model was the greatest contributor to the variance of basal area predictions for all ecotypes. When the stochasticity of this sub-model was disabled, the total variance decreased by 35% to 60% at the end of the projections.

Conclusions

This study is an example of uncertainty estimation of forest growth predictions at the regional level. The originality of our work includes the time perspective in the context of hybrid inference, the variance decomposition information and flexible methods, adaptable to different ecotypes and complex growth models. Our findings revealed that the extent of sampling- and model-related variance is a function of time. Sampling error is the most important source of variance in short-term predictions, while in long-term predictions, the model contribution is almost as important as that of the sampling. By decomposing the variance, we were able to point out that the mortality sub-model should be the target of our effort to reduce the variance since it has the greatest contribution to the prediction variance.

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REMOVING BIAS FROM LIDAR-BASED ESTIMATES FOREST CANOPY METRICS: ACCOUNTING FOR THE EFFECTS OF PULSE DENSITY, FOOTPRINT SIZE AND BEAM INCIDENCE ANGLE

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Airborne laser scanning (LiDAR) is used in forest inventories to quantify stand structure with three-dimensional point clouds. However, the structure of point clouds depends not only on stand structure, but also on the LiDAR instrument, its settings, and the pattern of flight. The resulting variation between and within datasets can induce spurious variation in LiDAR metrics. We present two hypothesis-driven models that can be used to correct bias attributable to 1) variation in pulse density and footprint size on canopy height (Roussel *et al.*, 2017) and 2) beam incidence angle on the vertical structure of the point clouds (Roussel *et al.*, 2018).

We first compared two LiDAR datasets acquired over the same forest with different parameters and observed that maximum height and mean height of the canopy surface model were 56 cm and 1.0 m higher, respectively, when calculated using the high-density dataset with a small footprint. Using probability theory, we developed a model that can predict the observed bias and that enables users to recompute the metrics as if the density of pulses were infinite and the size of footprints equivalent.

Secondly, we modelled the effect of scan angle on the vertical structure of the point clouds. This allowed us to predict the bias of metrics derived from the vertical structure of the point cloud for locations sampled off-nadir. We then compared the results of our model with paired observations obtained from off- and at-nadir assessments of the same point from different flight-lines. The model accurately reproduced the bias of all nine tested metrics calculated for a northern hardwood forest with relatively continuous canopy.

This modelling effort is our first step in developing methods for correcting various LiDAR metrics that are used for area-based prediction of forest stand structure. Such corrections may be particularly useful for multi-temporal LiDAR assessments.

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EXTENDING THE RANGE OF APPLICABILITY OF THE HYBRID ECOSYSTEM MODEL PRELES FOR VARYING FOREST TYPES AND CLIMATE

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Introduction

PRELES (PREdict Light-use efficiency, Evapotranspiration and Soil water) is a hybrid ecosystem model that predicts daily gross primary productivity (GPP), evapotranspiration (ET) and soil water (Peltoniemi *et al.*, 2015). The objective of the study is: 1) testing the applicability of PRELES model on a larger geographical scale; 2) proposing a generic set of model parameters for each forest-climate type and quantify the differences between sites while fitting model with pooled data; 3) quantifying the uncertainty of predictions when extrapolating to conditions outside the original sites.

Materials and methods

The meteorological and eddy covariance data were acquired and shared by the FLUXNET community.

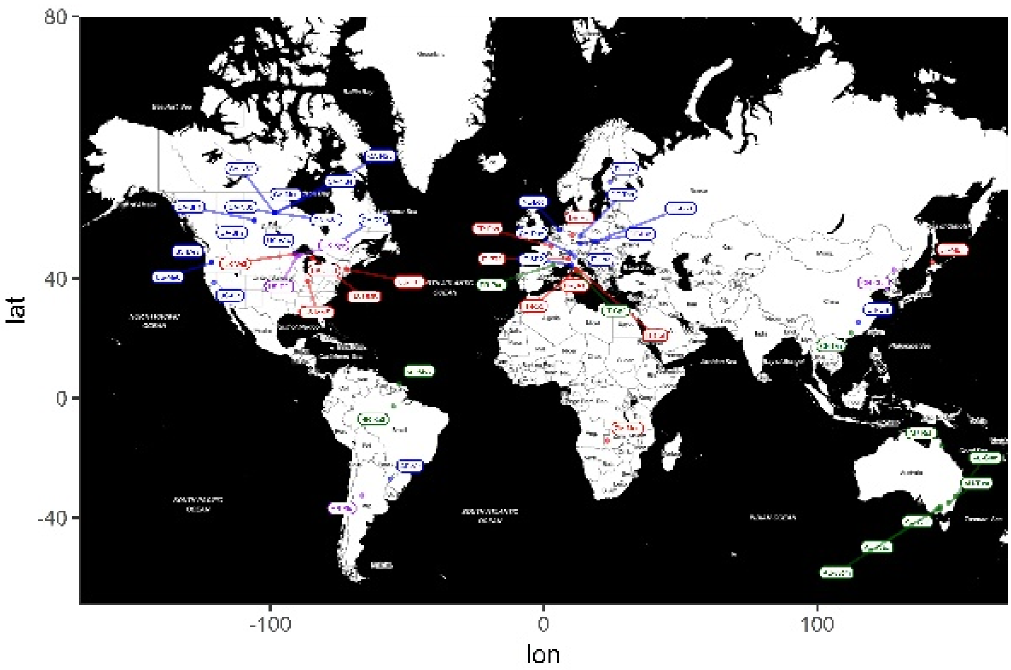

Figure 1: Study sites

Statistical calibration of PRELES model parameters was accomplished by Bayesian calibration. We implemented two kinds of calibration: site-specific calibration and multi-site calibration. For the site-specific calibration, model of each site was calibrated independently. For multi-site calibration, 55 sites were grouped into several clusters, and then a generic model was calibrated for each cluster using the Bayesian hierarchical modelling method. The grouping criteria are forest types and Köppen-Geiger climate classification.

Results

Three different version of PRELES parameters were generated in this study: site-specific calibrated version, multi-site calibrated with the site-specific light use efficiency parameter, and multi-site calibrated with random effects of light use efficiency parameter and measurement uncertainty. Each version is more generic than the former one.

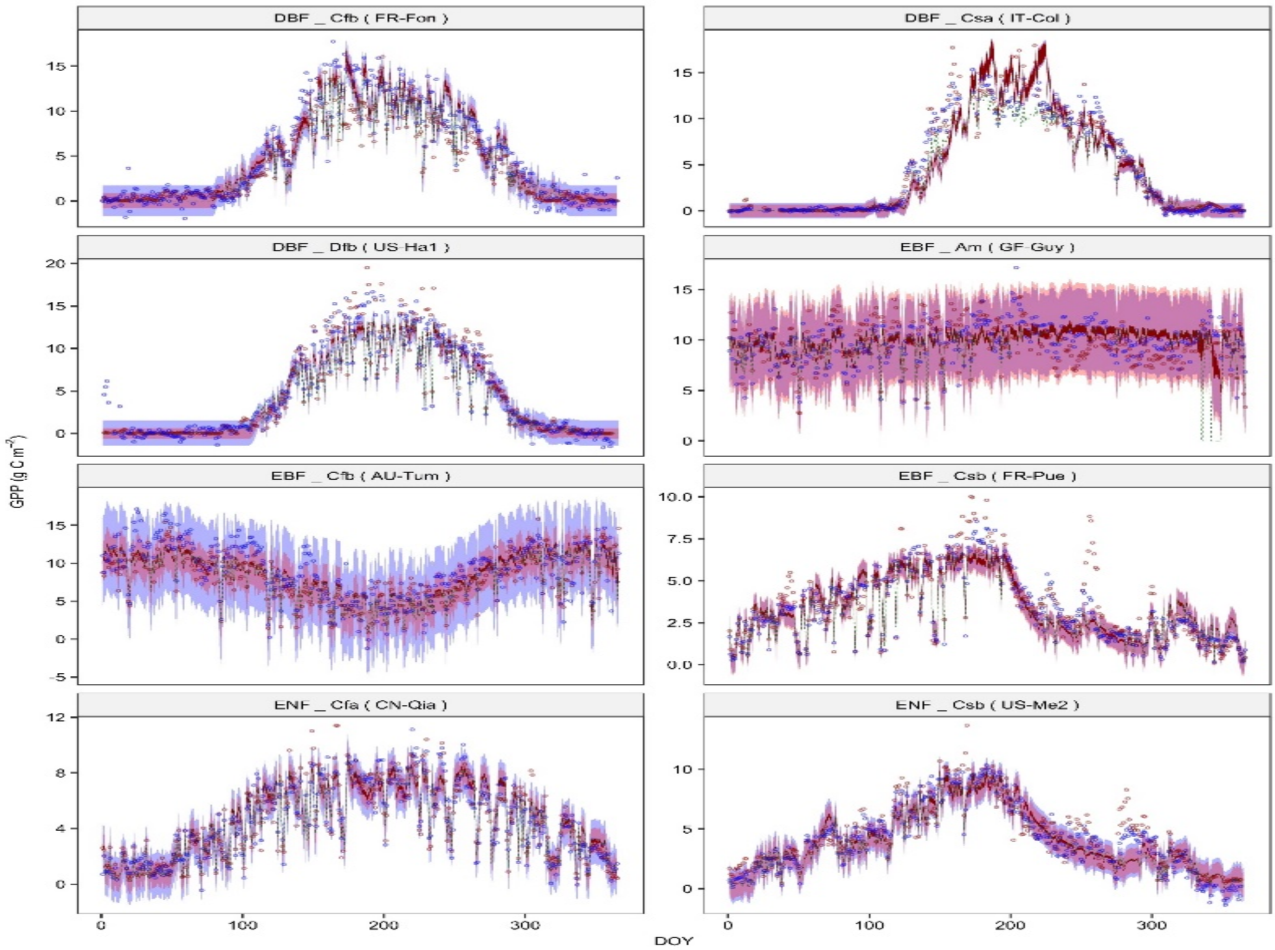

Figure 2: Daily gross primary production simulations for eight forest-climate clusters. One site and one year are randomly selected from each cluster. Red circles represent observations based on the daytime partitioning method, and blue circles are based on night-time partitioning method. The areas represent the uncertainty from the multi-site calibrated model. Dark red areas represent the simulations that only contain parameter uncertainty. Light red area represents the predictive uncertainty given by parameter uncertainty and daytime partitioning method measurement error, while light blue area is the predictive uncertainty given by parameter uncertainty and night-time partitioning method measurement error. The green dashed line is generated by the site-specific calibrated model with MAP (maximum a posterior parameter vector).

Limitations of forest production vary with forest type and climate condition. The impacts of environmental factors on GPP were described by the modifiers in the PRELES model.

We quantified the deviation between model predictions and two types of observations respectively for daytime-based observations (DT) and night-time-based observations (NT). The choices of data for calibration have also an impact on annual GPP and ET estimation.

Conclusions

The PRELES model is applicable in most temperate and continental climate and forest types.

Without consideration of random effects, it may underestimate with a large uncertainty when extrapolating the model to large regional simulations.

A dataset that contains observations on various possible climate conditions is preferred in the calibration, which can decrease the uncertainty of model parameters.

The accuracy of eddy data and the choice of portioning methods will affect prediction uncertainty.

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REVISITING SPACE-FOR-TIMESUBSTITUTION TO PREDICT FOREST PRODUCTION UNDER CLIMATE CHANGE

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Introduction

Predicting forest production under climate change scenarios is an up-to-date and relevant issue in forest growth and yield modelling. Robust and reliable predictions of forest production are decisive for decision making on effective management measures in forest stands. Furthermore, prediction of forest production is a modelling challenge, as forest yield is the result of long-term accumulative production processes, determined, limited and driven by multiple interacting endogenous and environmental factors which themselves and also their relative importance vary over time. Moreover, in managed forests we may differentiate between actual, achievable and potential yield of forest production, increasing the scale of degrees of freedom to the model scenarios and predictions.

Due to a lack of real times series, many empirical forest production models rely on the space-for-time substitution (SFTS) approach (Pickett, 1989). The basic assumption underlying SFTS is that the growth response across a spatial environmental gradient is analogue to the dynamic growth response over time (Evans, 1994). Because of the widespread use of SFTS systematic examination of the validity of the underlaying assumptions is needed (Rastetter, 1996; Tilman, 1989).

Here we present a critical discussion of the concept and underlying assumptions of SFTS and an empirical test of its validity based on an extensive longitudinal growth data set.

Materials and methods

The discussion and literature review consider contributions form forest growth and yield science, forest growth modelling, forest production ecology as well as from general ecology, with the scope to link traditional (e.g., Assmann 1970) with modern terminologies and approaches in forest site productivity research (e.g., Landsberg & Sands 2011; Weiskittel*et al.*, 2011).

The validity of the SFTS approach is tested using site index data of Norway spruce (*Picea abies*) in Southwestern Germany. The growth data are of longitudinal nature, i.e., they combine time series and cross-sectional data. The data originate from periodically repeated tree- and stand-level measurements on more than 600 regionally scattered permanent forest research plots, with the oldest measurements dated back to the end of the 19th century (Yue *et al.*, 2014, 2016).For testing the validity of SFTS we comparatively analysed spatial variation in site index and its changes across environmental gradients (SFTS) versus real time series of dynamic changes in site index under conditions of climate change.

Results

The application of SFTS to predict forest production under climate change is revisited in light of recent research findings (Yue *et al.*, 2016). Site index changes across spatial climatic gradients largely differ from dynamic site index changes under conditions of changing climate. Based on measurement data from long-term forest research plots in Southwestern Germany, we could not verify the analogy in growth response of Norway spruce to growing season temperature between space and time.

Conclusions

According to our findings, the application of SFTS for the prediction of forest production under climate change would produce largely misleading results. In order to reduce the error of predictions, important prerequisites are the availability of repeated measurement data from long-term forest research plots treated and distributed according to a proper model-based design, and the application of adequate statistical models which exploit both, the spatial and temporal as well as the tree- and stand-level information in these data. An updated conceptual framework of forest production potentials is helpful to evaluate the potentials and limitations of SFTS in a systematic way.

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A DYNAMIC STATE-SPACE SPECIFIC GRAVITY MODEL FOR LOBLOLLY PINE USING DATA ASSIMILATION TO IMPROVE WOOD PROPERTY ESTIMATES WITH EXPLICIT UNCERTAINTY

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Introduction

Intensively managed loblolly pine (*Pinustaeda*) yields merchantable volumes at younger rotation ages, which allows companies managing the species to reduce the harvesting age to increase stand profit and reduce risk. As a consequence, this reduction in rotation age results in a progressive increase in the proportion of corewood and thus a reduction inwood specific gravity (SG), mainly due to a lower proportion of latewood.

Materials and methods

To quantify this effect, we executed a study to model ring-level properties (width and SG). Ninety-three trees from 5 stands between 24 and 33 years of age were harvested and disks cut between log ends, which in turn were cut into 490 pith-to-bark radial strips. Within-tree values of SG and ring width were measured by X-ray densitometry. Overall, the measured properties were highly variable, particularly in rings close to the pith. Rather than using traditional mixed-effects models, a new modelling framework was developed to predict SG. Data assimilation using an extended Kalman filter was used to separate measurement from process noise, which allowed us to explicitly quantify the uncertainty related to the process.

Results

The Kalman filter approach resulted in a much higher log likelihood values (-2,302) compared to a mixed-effects model (-3,124) (Dahlen*et al.*, 2018). Additionally, the model is dynamic, which allows for silvicultural treatments effects, such as thinning and fertilization, to be easily incorporated into the model (Figure 1).

Conclusions

The resulting model was used to predict within-stem variation of annual ring width and specific gravity over time and represents a step forward in integrating wood quality models into growth and yield systems for loblolly pine.

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Dahlen, J., Auty, D., Eberhardt, T., Montes, C. 2018. Models for predicting specific gravity of intensively managed loblolly pine and their implications over a rotation. Forests, In Preparation.

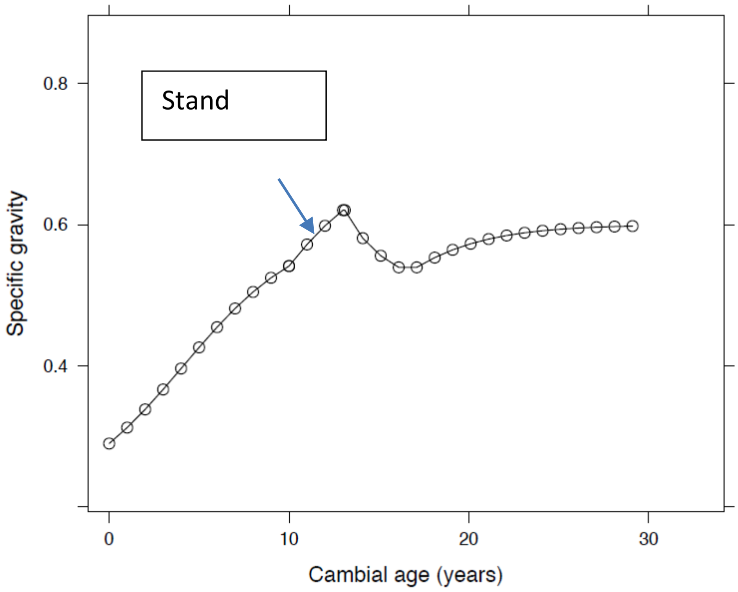

Figure 1: The dynamic model using the Kalman filter allows the incorporation of silvicultural treatments at the ring level.

WHAT DATA ACCURACY SUFFICES FOR STAND MANAGEMENT DECISIONS? A SIMULATION STUDY CONSIDERING DIFFERENT SITES AND INTEREST RATES FOR SCOTS PINE

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Introduction

The use of airborne inventory data to detect and delineate individual trees and to predict total tree diameter distribution (DD) has been studied a lot in recent years. However, it is unclear if the current methods produce a sufficient accuracy for forest management decisions. Even if some studies in this field exist, these are limited to even-aged forestry. The aim here is to study the implications of varying accuracy of inventory data up to the next management activity, depending on a wide set of alternatives also including thinning from above. The study is carried out by simulating DDs with varying shapes and scales, assuming the representation of the individual trees to be the main determinant of the related decisions (Vastaranta *et al.*, 2011).

Materials and methods

The simulations were based on altogether 40 pure Scots pine stands studied by Vauhkonen and Mehtätalo (2015). AllDDs were described using the two-parameter form of the Weibull function. Reference DDs were obtained by fitting the Weibull function to the trees measured in the field plots. Varying accuracies for the DDs were obtained by applying three different airborne inventory approaches to the same plots (Vauhkonen and Mehtätalo, 2015):

1. Individual tree detection and estimation, in which tree crown segments were isolated using an adaptive filtering of local height maxima and watershed segmentation. Tree diameters were obtained using a locally fitted model with maximum height and radius of the segments as predictors.

2. Area-based approaches based on polynomial regression models to correct the censoring effect caused by overlapping tree crowns in the above data. Both the population-averaged and localized models of Vauhkonen and Mehtätalo (2015) were tested for this purpose.

In addition, linear interpolation between the reference and predicted distribution parameters was used to generate a wider set of distributions that varied in terms of accuracy. In all alternatives, tree heights were predicted by the same, locally-fitted function. Using the diameter and height, the total stem and assortment volumes were estimated based on taper curves and a simple method mimicking stem bucking into logs for saw timber and pulp wood based on the same rules for allowable log lengths, their minimum diameters, and prices as used by Vauhkonen and Pukkala (2016), based on the specifications of roadside-transactions carried out in this area.

Altogether seven different management alternatives were simulated for each of the tree lists described above. The alternatives included no-management, clear-cutting, thinning from below, and four different thinnings from above, based on different rules for tree selection (Pukkala *et al.*, 2015; Vauhkonen and Pukkala, 2016) and therefore different distributions of the harvested and remaining trees. Except for simulating the management alternatives for the different forest structures represented by the 40 plots, each plot was simulated as if it was located on three different sites (either on *Myrtillus* [mesic], *Vaccinium* [sub-xeric], or *Calluna* [xeric] site types) and using interest rates of 2–4%, which affected the productivity of the remaining tree stock and also tree selection rules in some harvesting alternatives.

The results of the treatments for the different forest structures were evaluated in terms of two criteria: the present value of the harvested trees and the expectation value based on the bare land and the remaining trees. The present and future values were summed together and the management alternative that produced the highest total value was considered as the most suitable for the plot. The dispersion of the selected alternatives was examined as a function of the accuracy of DD under different site types and interest rates.

The present value of the harvested wood (€/ha) was obtained as price × quantity of the obtained timber assortments minus estimated costs of cut-to-length-logging and roadside-transportation of the trees marked to be harvested. The costs were estimated by modelling the time expenditure of these operations as a function of harvesting type (final felling vs. thinning) and the total removal. The time expenditure was multiplied by the unit cost assumed for operating a harvester and a forwarder in the relevant area.

The SEV was the present value (€/ha) of the costs and revenues resulting from timber production in the remaining tree stock, when its management rotations are expected to continue in perpetuity. The SEV was obtained as an average from a very high number of simulated rotations, in which the stand treatments were optimized for timber production with the given site fertility, growing stock and operational environment (temperature, interest rates and prices) related parameters.

Results and Conclusions

Even if simulated on simple Weibull function forms, the different harvests resulted in different distributions of harvested and remaining trees, which differed depending on the quality of the DD predictions. However, complex interactions between site fertility, interest rate, and initial forest structure also affected the harvesting outcomes based on the reference and predicted distributions. The presentation will provide a detailed account of these effects that cannot be presented in this limited space.

When pooled over all combinations of DDs, site fertilities, and interest rates, the predicted management alternative matched precisely that of the reference distribution in altogether 77% of the plots or did not otherwise cause losses in terms of the total SEV. However, management alternatives predicted on 5% of the plots would have caused losses corresponding to at least 6% of the total SEV and as much as 35% at maximum. The biggest losses did not occur with a specific inventory method or forest structure, but were related to the highest interest rates. Developing knowledge-based rules on management alternatives selected on different site fertility – interest rate combinations based on the reference data allowed for preventing the simulation of infeasible alternatives. A set of simple rules halved the proportion of highest SEV losses presented above.

The accuracy of forest inventory methods for selecting management alternatives for Scots pine stands was found adequate. However, because the decision of stand management is dependent on many other aspects than stand structure, it is recommended not to separate but to integrate the inventory and planning systems for well-informed decisions.

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CONSTRAINING PRODUCTIVITY AND CARBON CYCLE PREDICTIONS OF FINNISH FORESTS. DATA ASSIMILATION OF COUNTRY WIDE PERMANENT GROWTH EXPERIMENTS AND NATIONAL FOREST INVENTORY

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Introduction

Process-based forest growth models (PBM) play a role in the estimates of Earth's carbon cycle since they allow incorporation of information about actual forest structure and management practices. However their reliability depends on model structure, calibration and predictive uncertainty. The main objective of this work was to calibrate a forest growth model (PREBAS) using an extensive dataset that covered a wide range of climatic conditions, species composition and management practices across Finnish forests. PREBAS was calibrated for the three main commercial species in Finland: Scots pine, Norway spruce and silver birch. Our specific objectives were to ascertain if a generic species-specific calibration can be found, to perform a sensitivity and uncertainty analysis, to run the model at country-level showing the potential for stand growth and carbon balance predictions.

Materials and methods

PREBAS is a process-based growth model that combines a light use efficiency model (PRELES, Peltoniemi *et al.*, 2015) and a tree growth model based on the pipe theory (CROBAS, Mäkelä, 1997; Valentine and Mäkelä, 2005).

Two types of datasets were used for model calibration:

(1) Finnish National Forest Inventory (NFI), established by the Natural Resources Institute Finland (LUKE), consisting of 137 sample plots, including 223 species-plot subsets of Scots pine, Norway spruce and silver birch.

(2) Long-term growth and yield experiments (PGE) set up by LUKE to investigate the effects of thinning intensity on growth and yield of the stands; the data set consisted of 785 plots of which 128 were Norway spruce dominated and 657 were Scots pine dominated.

We used the Bayesian method to estimate model parameters in terms of probability distributions (posterior distribution), quantifying parametric uncertainty.

For assessing the geographic trends in growth potential predicted with the PREBAS model, we made simulations from an initial seedling stand over the whole rotation for pine and spruce stands on sites of four different fertility classes, over a country-wide grid with resolution of 1 km x 1 km. The output of these simulations was compared with national forestry statistics (Finnish Statistical Yearbook of Forestry, 2014)

Results

By means of Bayesian calibration we assimilated multi-site, multi-experiment and multiple type of data in the model. We reduced the parametric uncertainty of PREBAS and calibrated the model for three forest species. Model output uncertainty was strongly reduced.

PREBAS reliably predicted the data from NFI and PGE. The goodness of fit was better for average stand height and average diameter predictions than those for basal area, stemwood volume and height of the crown base. Furthermore, the PGE calibration performed better than the NFI calibration.

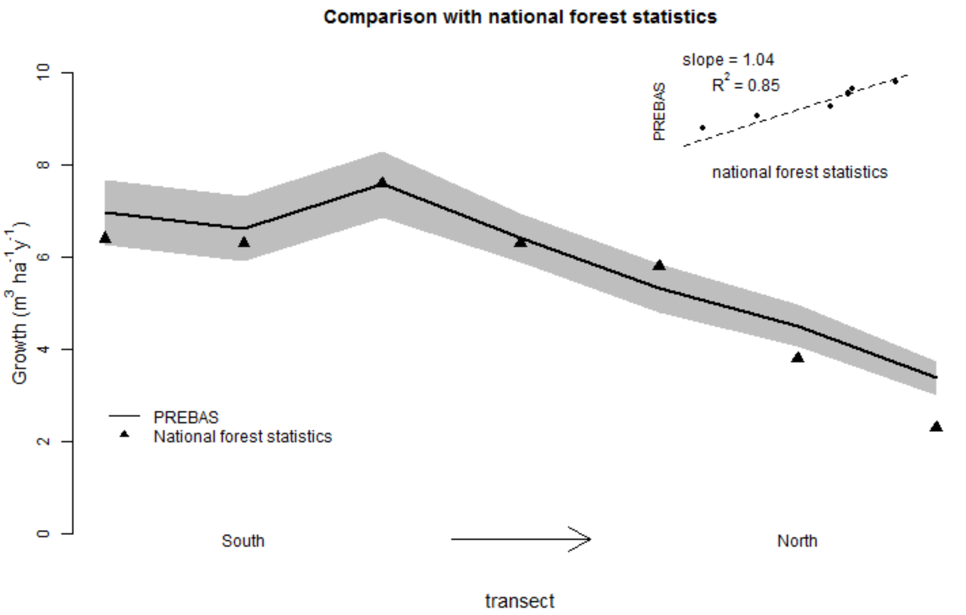

Figure 3: Comparison between Finnish national statistics of forest annual growth (triangles) and PREBAS predictions (black line). The shaded grey area represents model predictive uncertainty. National statistics estimates were taken from the regions where the transect points were located and were computed for pine and spruce. Model predictions were the weighted average MAI of pine and spruce at different growth sites, where the weights were obtained from the National statistics based on respective areas covered in each region.

For forest growth and timber production a latitudinal gradient was found moving from North to South, due to the climatic conditions. The South-West part of the country resulted the most productive area. MAI estimates were sensitive to site fertility class; in fact, the average country MAI, decreased by about 1 m^3 ha^{-1} y^{-1} moving from the more fertile to the less fertile soils

PREBAS estimates of MAI were consistent with the national forest statistics for timber production (figure 1). PREBAS overestimated MAI in the northernmost part of the country, while MAI predictions were in close agreement with the national forest statistics, showing a higher peak of MAI in central Finland.

In general, the PGE data were able to constrain the posterior distributions much more than the NFI data. The key parameters that remained uncertain in the PGE calibration were those for which direct data were not available, e.g., the respiration parameters, the coarse root ratio, and wood density. Additional data on process-related variables, such as foliage and fine roots, should prove useful for improving the parameter estimates for the carbon balance.

We found that the predictive uncertainty (i.e. parameter uncertainty + error uncertainty) was dominated by the error uncertainty. In our representation of the error, the model structural error (discrepancy) and the data error are lumped together, leading to an overestimation of the uncertainty since we are including the stochastic error of the measurements in the predictions. Our results suggest that to reduce the predictive uncertainty we should improve the structure of the model, reducing the discrepancy, and also we could collect more accurate data reducing the measurement uncertainty.

Conclusions

- By means of Bayesian statistics we were able to calibrate and test a forest growth model based on the pipe theory. The data assimilation of multiple data types, sites and species allowed us to make use of tree measurements collected over decades. Furthermore, thanks to the Bayesian framework, our posterior distribution can be the prior for a new calibration when new data will become available.
- Model reliably predicted stand variables of pine, spruce and birch forests across Finland under a wide range of management and environmental conditions, proving to be a robust tool for regional analysis and forest forecasts.
- Uncertainty of model parameters and output variables was strongly reduced after the calibration.
- Posterior predictive uncertainty of the model was mainly influenced by the uncertainty of the structural and measurement error.
- Permanent growth experiment dataset led to a more robust calibration than the national forest inventory dataset. PGE calibrated PREBAS showed better predictive performances and lower estimates of uncertainty for forest growth variables.

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STAND HEIGHT GROWTH MODEL CONDITIONED TO CHANGES IN RAINFALL FOR EUCALYPTUS PULPWOOD IN MONDI SOUTH AFRICA

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Introduction

Accurate measures of site productivity of forest stand are key to predicting forest growth and yield (Sharma *et al*., 2015). Dominant height, defined in South Africa by Bredenkamp (1993) as the average regression height of the twenty percent thickest trees, is commonly used as measure of site productivity. The Chapman-Richards model, both in guide curve and difference form has been commonly used in forestry to model dominant height as a function of age. On average, the application of this function is acceptable. However, there is one major drawback associated with the current approach of using age as the only independent variable in the model. Climatic effects, particularly rainfall, is not accounted for in the model, and rainfall is one of the factors affecting growth. For short rotations, such as gum pulpwood, one extreme rainfall event such as drought, is more than sufficient to compromise the application of this model. Most alarming, in such a case, the impact of drought cannot be quantified, thus making it difficult to adjust growth estimations accordingly. This is a growing concern and there is no known study in South Africa to address this challenge.

The introduction of modifiers will provide two major benefits, namely: 1) an option to adjust site index estimates and; 2) an option to adjust growth rate given a calibration point. The objective of this study is to achieve the first benefit. In particular, to present an example to introduce the rainfall effect in the height growth model so that the site index estimate can be sensitive to changes in rainfall. The approach in this study is inspired by Scolforo *et al.* (2016).

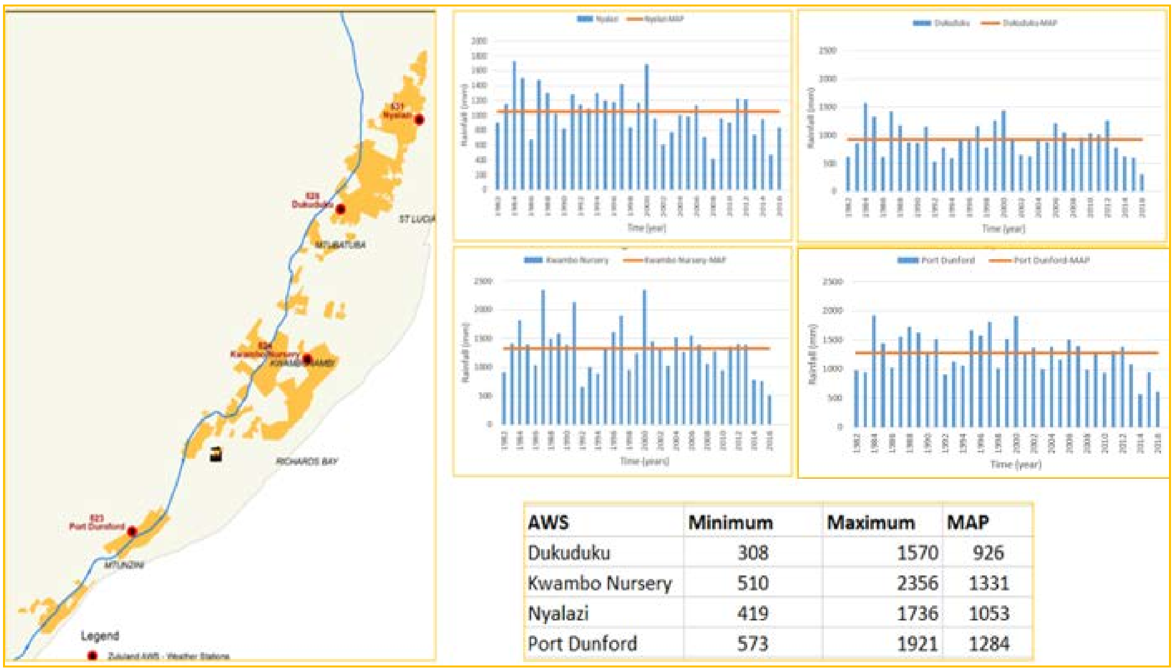
Materials and methods

The growth and climate data were sourced from the permanent sample plots (PSPs) database and four weather stations, respectively. In particular, the *Eucalyptus grandis x Eucalyptus urophylla* (*E.gxu*) PSP data in Coastal Zululand were used. The rainfall data were obtained from Kwambo Nursery, Nyalazi, Dukuduku and Port Dunford weather stations. The plantations and weather stations are displayed in Figure 1.

The Chapman-Richards model to be used is defined as follows:

$$H(t) = A.[1 - \exp{(k.age)}]^c$$

where *A* is the final (asymptotic) size of tree; *k* reflects the growth rate of trees when *H*(*t*) increases from *age*=0 to *A* and *c* is the anabolism rate which controls the shape of the curve and the location of the inflection point.



AWS	Minimum	Maximum	MAP
Dukuduku	308	1570	926
Kwambo Nursery	510	2356	1331
Nyalazi	419	1736	1053
Port Dunford	573	1921	1284

Figure 1: A map of all Mondi plantations in coastal Zululand with rainfall information.

The modifying factor as a function of climate can be defined as:

$$mod = A/(1 - b_1 R) + \varepsilon_i$$

where *mod* is the modifying factor of asymptote; A is the asymptote of the Chapman-Richards model; $b_1$is a regression parameter; *R* is cumulative rainfall from plant date;ε_i is a random error. A similar approach was adopted by Nunes, *et al.* (2011). This modifier determines the contribution of rainfall to the improvement of the model. Thus, the resultant formulation of the Chapman-Richards model is:

$$H(t) = mod.[1 - \exp(k.age)]^c$$

The Chapman-Richards model was fitted using the proc nlin procedure in SAS, with and without the modifier to determine whether the modifier improved the model. The model performance was evaluated using adjusted R-square, the root mean square error and bias.

Results

The preliminary analyses indicated that the effect of rainfall was significant on height growth. The rainfall modifier was included in the Chapman-Richards model.

The model was assessed for validity and predictive ability. The model was found to be valid. The residual analyses indicated that the model assumptions were not violated.

Furthermore, the resultant model was assessed to determine whether it behaves logically, by plotting the model over time with different cumulative rainfall. This was to determine whether the model responds to cumulative rainfall. It can be observed in Figure 2 that the model behaves logically.

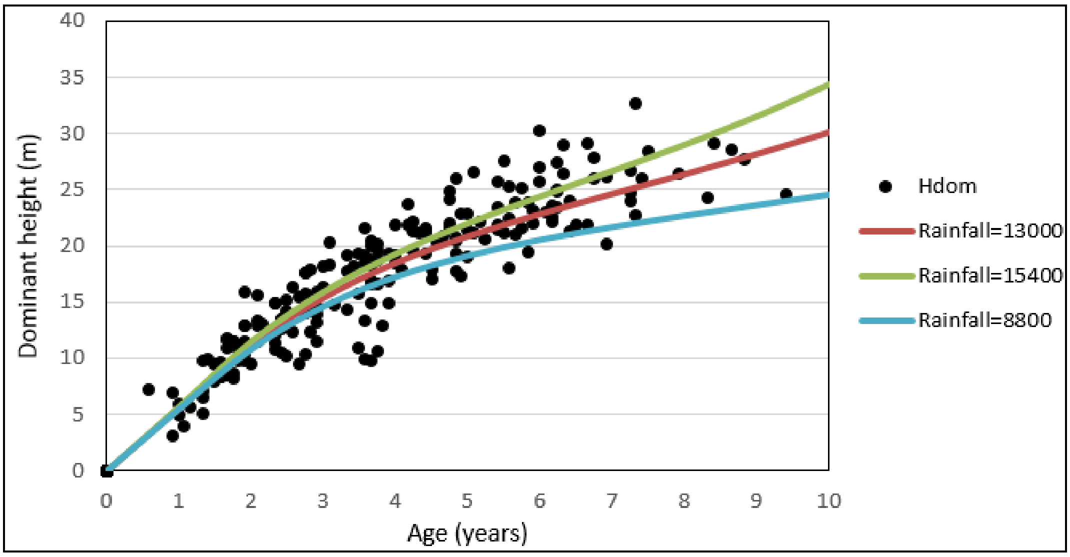


Figure 2: PSP dominant height over time modelled with different cumulative rainfall amounts.

Conclusions

The rainfall effect can be included in the height growth model by means of a modifier. This approach does not take anything away from the existing model, it simply adds a feature to allow the model to be sensitive to changes in climate. Furthermore, this approach does not violate model assumptions and therefore it can be considered.

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ASSIMILATING DOMINANT HEIGHT MODELS IN SPACE AND TIME TO REDUCEMEASUREMENT COST WHILE REDUCING OVERALL PROJECTION UNCERTAINTY

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Introduction

Tree height is one of the most expensive variables to measure when using ground inventories. Often, only a sub-sample of the plot trees are measured and then projected to a key age to predict plot site index values. This is done several times throughout the life of a stand, particularly for even-aged intensively managed plantations. To improve the estimated number of samples required during a new inventory, an ideal knowledge about the errors at the time of the new inventory would be helpful. It is reasonable to assume the variance from the previous sample will keep increasing over time due to random deviations caused by the environment, hence, this original variance would be of limited use to calculate the required sample size. Despite this belief, propagating variances with non-linear transformations result in biased estimates on the expected uncertainty. One solution is to apply linearly transformed growth equations to the previous observations to estimate actual variance values. However, there is still the question about the separation between observation errors and the one derived from the process of growing the trees. To overcome these limitations, we developed a parameter estimation approach using an algorithm commonly found in control theory, the Kalman Filter (Kalman, 1960), and we adapted it to account for nonlinearities in the process (Jazwinski, 1970)

Materials and methods

The non-linear filtering approach (extended-Kalman filter, eKalman) was implemented to find parameters for a dominant height equation, explicitly separating observation from the process error, to overcome the limitations imposed by traditional parameter fitting methods. The methodology was tested with a series of loblolly pine plantations in the south-eastern U.S. coastal plain. We compared our methodology with two other parameter finding methods found in the literature (a simple non-linear regression(NLR) using the guiding curve method to define the model (Brickell, 1968), the base age invariant (BAI) method by Clutter et all (1983), and the Dummy Variable (DV) method found in Cieszewski and Bailey (2000).The equations estimates were further assimilated with inventory plots present in a farm in Georgia using a non-parametric interpolator (thin-plate splines), to further correct predictions while reducing plot uncertainty.

Results

The methodology allowed the reduction in fitting statistics (AIC of -1464 compared to 3200, 2525 and 2868 in the non-linear regression, the BAS and the DV methods respectively). Variance projection values were the smallest for BA, followed by the eKalman, DV and NLR. An important reduction in projection error was used when combining previous height measurements with current measurements, reducing the overall uncertainty (Figure 1).

Conclusions

Our results compared with cross validation resulted in much better height estimates at rotation age, as well as a means to reduce the inventory cost by using previous observations in a statistically sound way. Examples are provided on the use of this techniques for data fitting, model projection, and inventory planning.

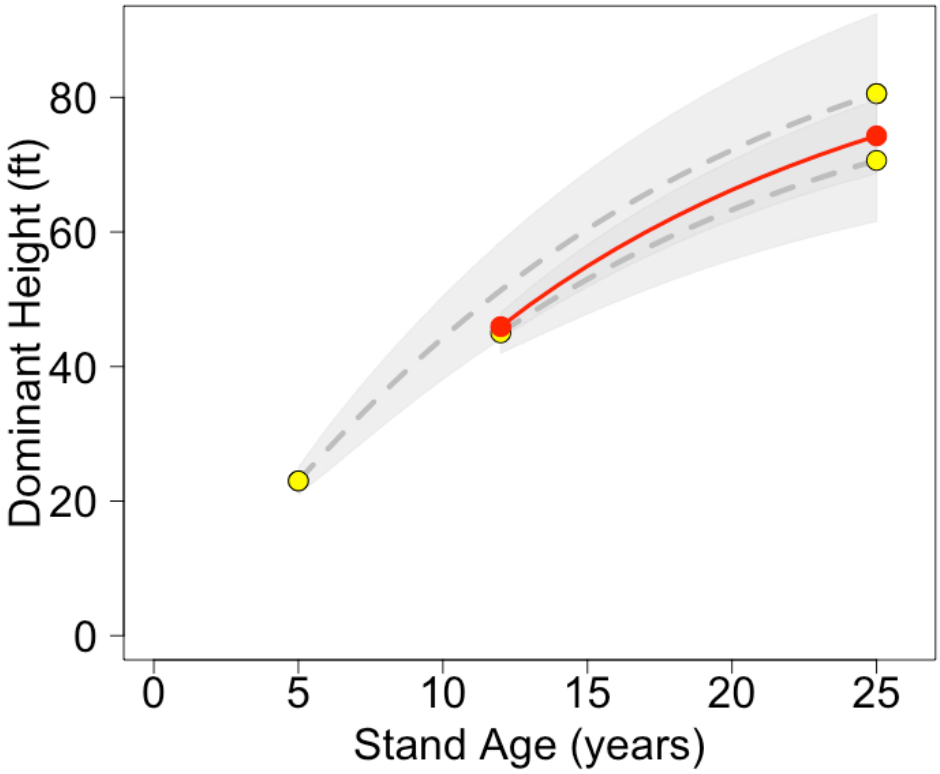

Figure 1: Dominant height prediction (ft) from previous inventory (year 5) and current inventory (year 12). The assimilated prediction (red) shows a smaller prediction interval.

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UNCERTAINTY IN DOMINANT HEIGHT AND SITE INDEX ESTIMATES IN A *EUCALYPTUS GRANDIS* PLANTATION CASE STUDY

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Introduction

Dominant height (HD) and site index (SI) values are important initial variables in the context of stand-level growth models widely used in fast growing plantation forests. Uncertainty inherent in these variables negatively impacts the usefulness and confidence of projections, planning and volume estimates and valuations (Berger *et al.,* 2014, McRoberts and Westfall 2014, Eid 2000). Multiple calculation steps are used to estimate HD and SI which are subject to multiple sources and types of error: i.e., measurement error, model error and projection error (*Figure 1*). These contribute to the uncertainty and inaccuracy that can be observed in SI and HD estimates and may interact resulting in error propagation towards the final estimate. This process is poorly understood, and the selection of HD definition and projection model are not usually chosen to minimise the effect of these errors. In addition, the accuracy of HD estimations is also influenced by model choice, i.e. the type of definition that is chosen to represent HD and the class of model chosen for the projection. For example, HD estimates can be affected by stand density (Ritchie *et al.,* 2012, du Plessis and Kotze 2011) which can introduce error into growth projections. Choices between the type, structure and fitting method of HD projection models can also have an effect, e.g. the choice between polymorphic vs anamorphic models (Rivas *et al.,* 2004)

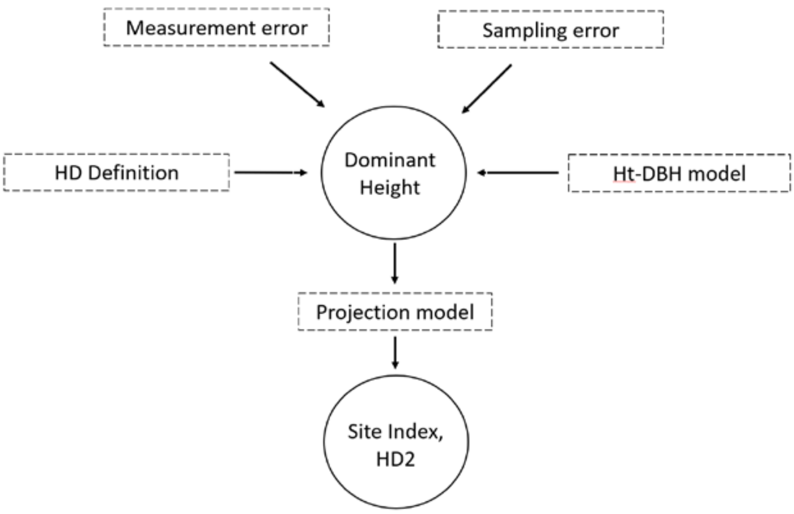

Figure 2: Conceptual model of the factors and estimation steps influencing the HD and SI (and projected dominant height HD2) estimations

The objective of this study is to measure the error of SI and HD estimates and to quantify the contribution of error to each component of the estimation process in a case study. Different methods can be used at each step and therefore the opportunity was used for a comprehensive review of methods for each, with a comparison of suitability of various HD definitions, HT-DBH (height-diameter) models and HD projections models. These steps follow a generally applied method of estimating HD and SI in a stand level growth model applied in South Africa. These will result in a test case of at least three suitable choices for each step which will be used in a case study on a PSP dataset (Permanent Sample Plot). This study will therefore demonstrate: (a.) the estimation of errors and the resultant effect of error propagation in a well-controlled case study, and (b.) the selection of a suitable HD estimation and projection methodology in the context of error propagation.

Materials and methods

Four sites were selected in which 2ha transects were installed in fast-growing *E. grandis* sawtimber plantations in the Tzaneen region of South Africa. All diameters at breast height (DBH) were measured in a standardised way using a caliper, the relative tree positions were recorded and a sample of 128 heights were selected to be measured in each transect. In addition, a comprehensive set of scans were performed across the areas at all site using Terrestrial Laser Scanner (TLS) using a Z+F 5010X scanner (*Figure 2*). The height samples were measured four times by different operators where DBH and Height measurement repetitions were recorded. An aerial laser scan was made in one of the four sites to reference an above canopy scan. The TLS scans were assumed to represent actual measurements of DBH and Height, against which to make reference for the "real" value of the trees against which manual measurements were compared to this to provide a database of measurement errors for use in the sensitivity analysis.

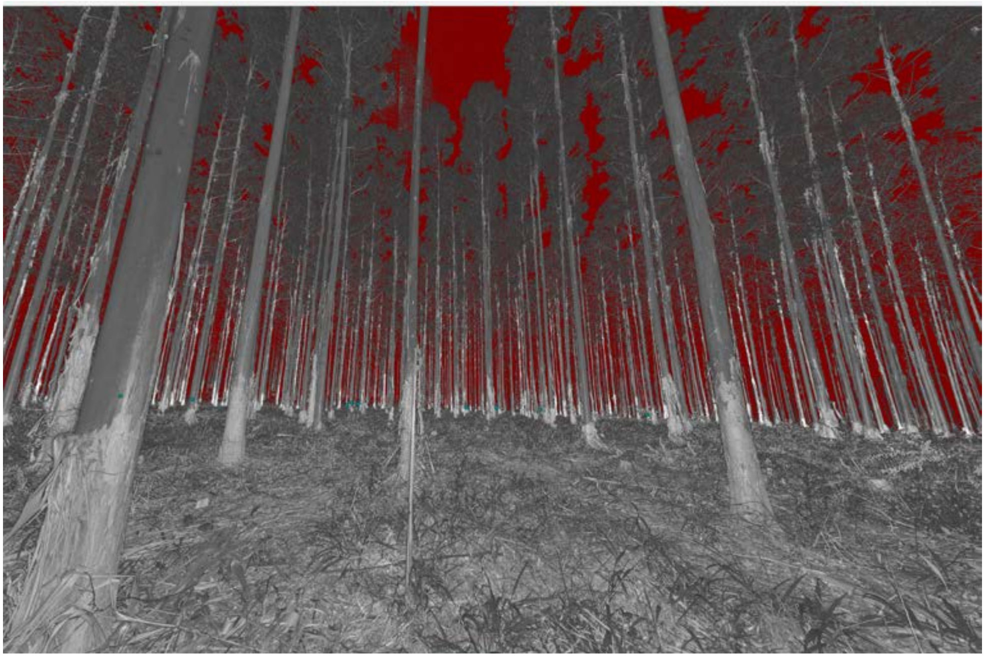

Figure 3: ***Terrestrial laser scan of one of the four fully measured sites***

Re-sampling simulations were performed within each of the 2 ha transects to quantify sampling error associated with various sampling methodologies (e.g. *Figure 3*).

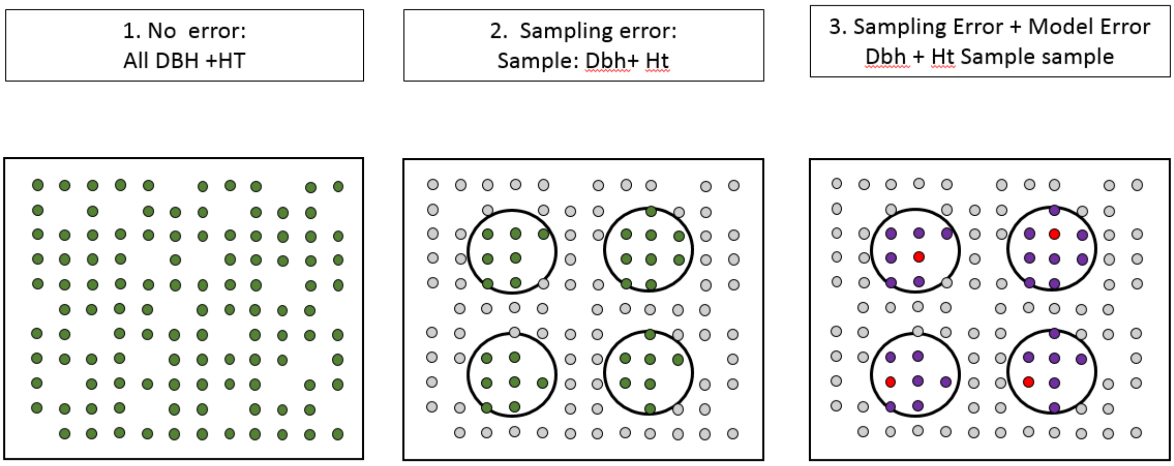

Figure 4: Illustration of the resampling approach to be undertaken on the measured transect, which will quantify sampling error and various other error propagation components within a traditional plot-based sampling approach.

For a review of model components, *E. grandis* CCT trials (Correlated Curve Trend) were used to compare the performance of HT-DBH regression methods, HD definitions and projection models, particularly with reference to how variable stand density would influence the error associated with these assumptions and calculations. Three HT-DBH models were selected, and four HD estimation methods were select together with three projection models for use in the PSP data case study. This step was used to filter out suitable candidate models that could be used in the PSP data analysis and to view the performance of HD models in varying stand densities.

The PSP dataset of the Tzaneen region was used as a case study where HD and SI uncertainty were created. From the selected model types, HD, HT-DBH and HD projection (and SI) models were fit on the PSP data. Error distributions from the controlled study were used to feed in measurement and sampling error into estimates. The HT-DBH, HD types and projections models were then used to predict HD (and SI) to future ages. These were references against the actual PSP measurements and the error level. This procedure is illustrated in *Figure 4*.

Results and Conclusions

This study is currently ongoing. Preliminary results show a clear increase of uncertainty in each estimation step in an error propagation.

HD definitions currently used in South Africa seem inadequate to cater for differing stand densities. Results of alternative HD definitions and projection model types fit on CCT trials in *P.elliottii* suggest that changing the definition to an absolute rather than a relative HD definition improves the accuracy and robustness of the models over differing stand densities and that using a Polymorphic model type increased the accuracy (Figure 5).

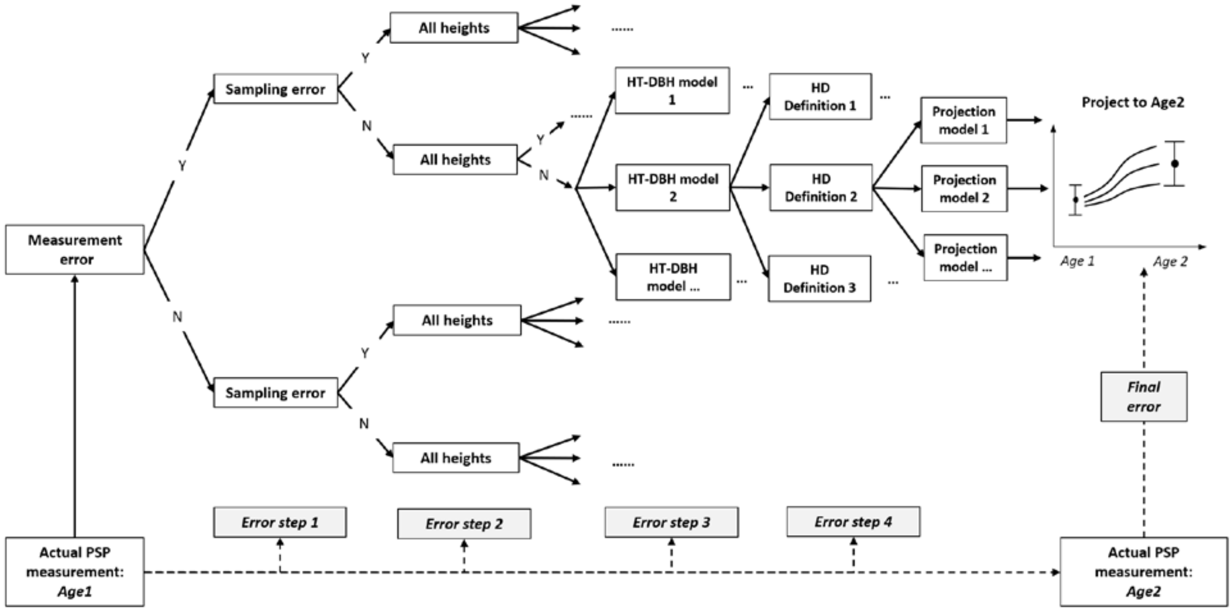

Figure 5: Conceptual model of the methodology used to measure uncertainty and error propagation for a full HD estimation and projection for the PSP data. The chart represents a decision tree with one path of estimation illustrated in detail. Grey filled bars represent measured error compared to actuals at each step which will form the results.

Results on uncertainty propagation thus far show that improvements can be made at each estimation point reducing the final total error, and that the relative contribution of each step should be clearly understood for planners and specialist to determine the best point at which to invest to reduce the uncertainty in predictions. Final results will be presented to how the contribution of error propagation at each step can be illustrated and improvements to calculation step using improved methods shown. This information will be useful for determining sampling strategies under the context of improving technology and for mapping and estimating uncertainty levels in planning estimates and valuations.

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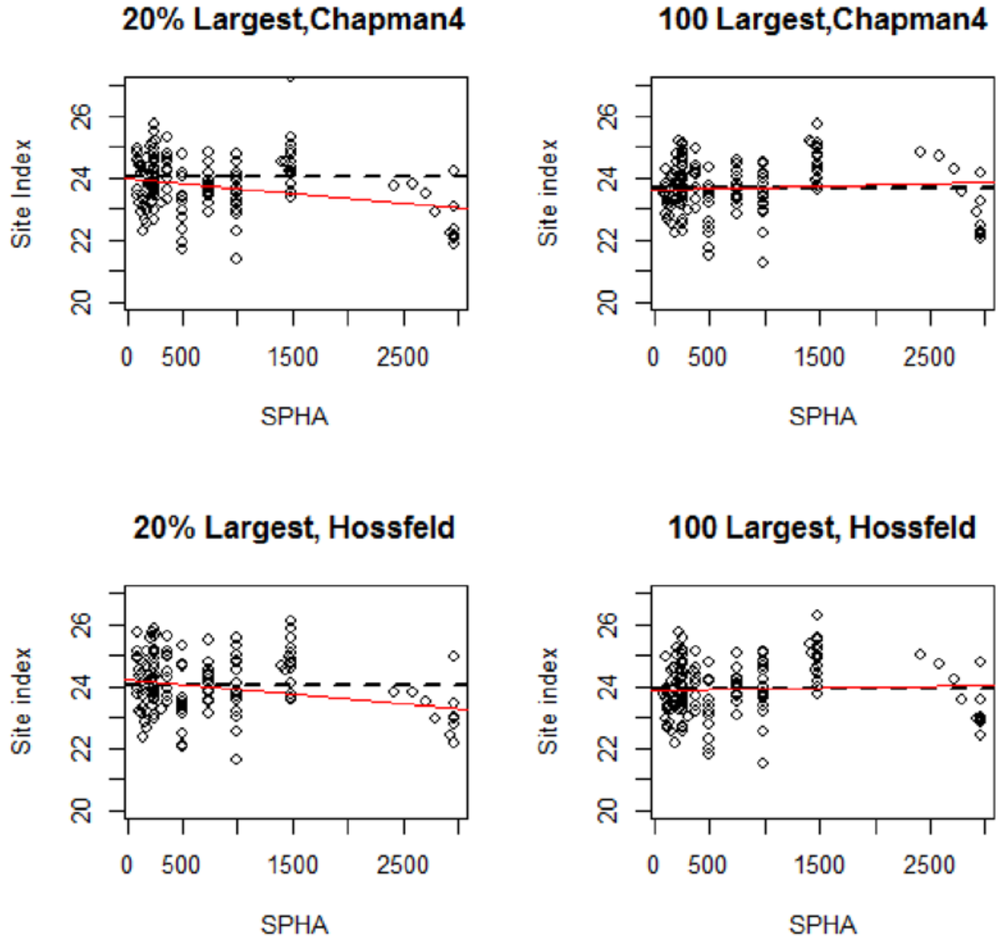

Figure 6: Example of alternative HD (relative 20% largest trees and 100 largest trees) and different model types (Chapman Richards 4 parameter and the Hossfeld IV polymorphic model). SI estimates are plotted over stems per hectare

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MODELING CLIMATE EFFECT ON CARBON SEQUESTRATION USING TREE RING MASS SERIES

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Introduction

Most forest carbon sequestration are estimated based on growth and yield models, usually without considering climate impacts and differences in wood/carbon density. Studies have shown that there exists a differential up to 20% in carbon stored in tree stems between species (Lamlom and Savidge, 2003). Ring width series (sequences) have been used as climate proxy to study past climate. This study looks into whether or not ring mass series would store similar climate information that could be directly used to forecast future carbon sequestration accurately.

Materials and methods

Data for this study came from SilviScan™ measurements on discs sampled at multiple heights of 35black spruce and balsam fir trees from boreal forests in Mauricie and Gaspésie regions of Québec, Canada. The SilviScan data included pith-to-bark sequences of ring width, density, and other wood and fibre properties. After cross-dating, measurements for the same ring at different heights were identified. Ring volume was estimated using ring width sequences at different heights, assuming a truncated cone between two consecutive heights and a cone between the highest disc and tree tip. Ring mass was estimated by summing the products of ring volume and average density of each section between two consecutive heights. After standardization using dplR package (Bunn 2008, 2010; Bunn *et al.*, 2018), ring mass sequences were compared with ring width sequences at breast height (BH). Chronologies were created using bi-weight robust mean estimation for each group of trees from close proximity (plot) that shared similar weather conditions and disturbances and subsequently evaluated for their correlation with climate variables (http://climate.weather.gc.ca/index_e.html) using treeclim (Zang and Biondi, 2015), PCA (Le *et al.*, 2008), and pls (Mevik*et al.*, 2016) packages in R (R Core Team, 2018).

Results

Although ring widths at the upper heights, particularly those near the pith, are greater than that of lower heights for the same ring, ring width profiles from all heights follow a similar trend of year-to-year variation (Figure 1). Mass profile also shows a similar rhythm of fluctuation to ring width (Figure 1).

Despite the marked differences in raw sequence profile between ring width at BH and ring mass/volume (Figure 2), the variations in ring indices after standardization were well captured regardless of which raw sequence (ring width or ring mass) was used (Figure 3) with some exceptions. Standardization removes low frequency growth trend from a ring sequence, allowing the impacts of external forces (climate, disturbances, etc.) to reveal. Standardization of the whole mass sequences was sometimes non-converging due to the near-zero mass values for rings formed at young ages (e.g., < 8-10 years), therefore these rings were pruned before the standardization. This should have limited effects on other rings, however, the information from these rings was lost.

As shown in Figure 1, ring width is generally greater at higher up positions. Intuitively this suggests the width of a ring is affected more by the height position at a tree trunk than by climate. However, since standardization removes growth trend and scales sequences to an average value of indices being one, the wider ring width at higher positions in the crown might not necessarily contain stronger or weaker climate signals. In addition, since rings at higher up positions normally have smaller diameters, they account for a smaller portion in total ring volume.

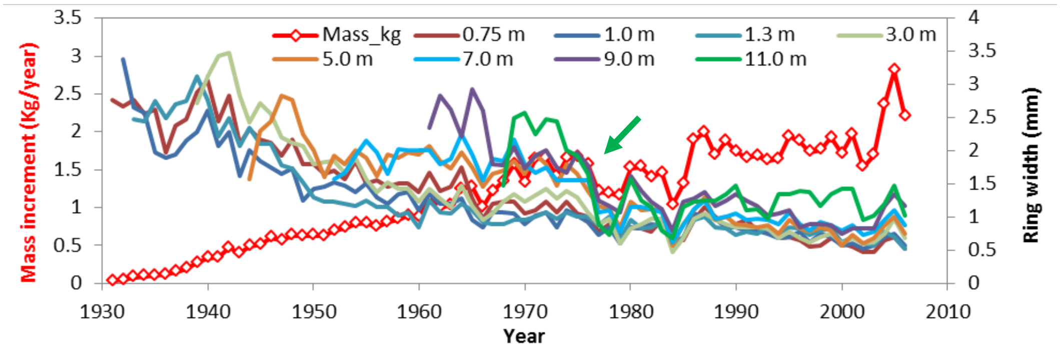

Figure 1: Ring width sequences at different heights and mass sequence of the same tree. Two or three rings near the pith are not shown. Green arrow: spruce budworm outbreak.

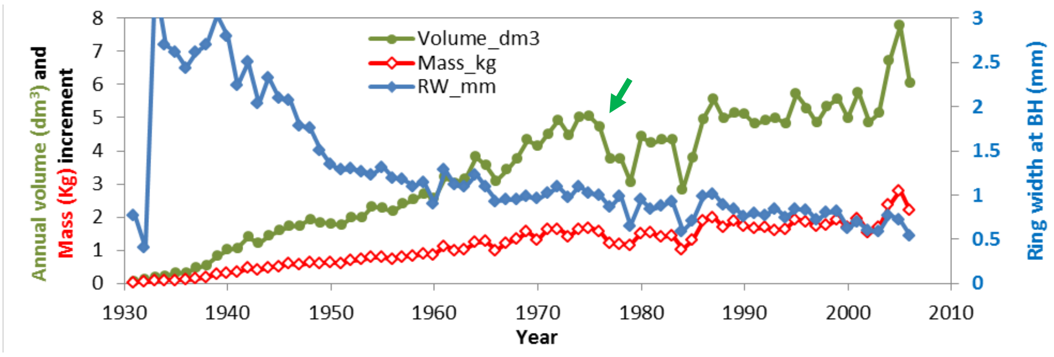

Figure 2: Raw sequences of rind width at breast height, volume and mass of the same tree. Green arrow: spruce budworm outbreak.

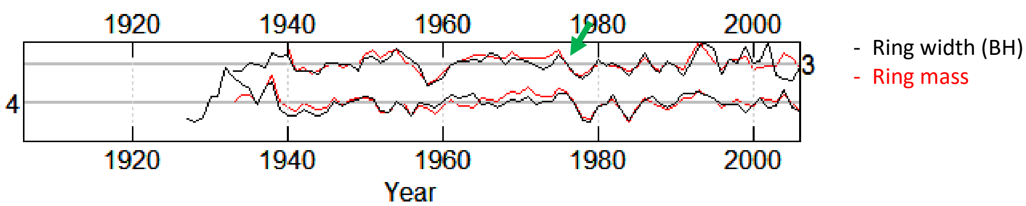

Figure 3: Standardized indices of ring width at breast height (BH) and mass of two trees. Green arrow: spruce budworm outbreak

Dendroclimatology analysis, principal component analysis (PCA), and partial least square regression analyses revealed a poor correlation between climate variables and tree ring mass chronologies with less than 5% explained variance for this sample set. A Y-Aware PCA method (Zumel, 2016) improved the explained variance to 56% for some plots where spruce budworm attacks in late 1970's were less severe. The poor correlation in this study suggests that while climate change may affect carbon sequestration in forests directly (e.g., slower or faster growth due to climate change), a more significant impact of climate change would manifest more indirectly, by causing more frequent and severer natural disturbances such as insect outbreaks, diseases, and fires.

Although the standardized indices from both ring width and mass sequences are similar (Figure 3), further work is needed to confirm whether tree mass sequence is equivalent to ring width sequences from higher up positions regarding climate change effect. Nevertheless, future forest forecasting warrants the inclusion of climate change and its resultant natural disturbances.

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QUANTIFICATION AND REDUCTION OF UNCERTAINTY IN PROCESS-BASED FOREST MODELS

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Introduction

Model-based projections of future forest dynamics are subject to considerable uncertainty even when based on mechanistic representations of ecological phenomena. Ensemble runs have frequently shown that future simulations can differ substantially among models, although model performance regarding observed past trends is often consistently good (e.g., Nishina*et al.*, 2015). Such uncertainties between models result from differences in model structures and formulations. In forest stand and landscape models that simulate demographic processes and interspecific resource competition for a large number of tree species on a spatial scale of square meters to kilometers, the level of complexity and hence the number of potential model formulations and parameterizations is large. Moreover, due to complex interactions and feedback mechanisms, even comparably minor differences in model formulation and parameterization may lead to noticeable differences in future projections (e.g., Elkin *et al.*, 2012). To better assess the predictive power of such models, it is crucial to better quantify the uncertainty that arises from different model formulations. However, such a study is missing for forest landscape models. In addition, novel methods are needed to increase the robustness of forest simulation models.

The study presented here is divided in two parts. First, we conduct the first systematic comparative study of forest landscape models to analyze and quantify the uncertainty in their future projections. Second, we show how model robustness can be increased by systematically applying a pattern-oriented modelling (POM) approach.

Materials and methods

In the first part, we applied four forest landscape models (iLand, LandClim, TreeMig, Landis-II) for the same European landscape (Dischma valley near Davos, Switzerland) using several past and future scenarios. External forcing factors were identical across all models. We analyzed simulated between-model differences in forest structure and composition, and quantified the variance explained by model differences using variance partitioning. In the second part, we compiled a list of alternative model formulations and parameterizations for all major demographic processes (i.e., growth, mortality, and regeneration) based on an extensive literature study. Using a full-factorial design, we subsequently tested the (in total 504) alternative model formulations under a wide range of scenarios using a POM approach. This means that we tested the performance of these model formulations in terms of their capability of reproducing short *and* long-term trends in both mixed *and* monospecific stands under different levels of *extrinsic disturbances* (managed, unmanaged old-growth, unmanaged but disturbed) under a wide range of site conditions across Europe.

Results and Conclusions

All forest landscape models were able to adequately reproduce the observed current forest structure and composition, but between-model differences in future projections over the next 100 years were substantial. For instance, while three models predicted strongly increasing total biomass with increasing temperature, one model simulated biomass losses under the same strong warming scenarios. In addition, the response to disturbances was model-specific, and both increasing and decreasing trends in tree species diversity with increasing frequency of disturbances were simulated. We show that for this type of models, structural differences between the models explain much more of the observed variance than differences in climate scenarios, clearly indicating that we need to put a greater focus on increasing the robustness of model projections.

The results of the second part suggest that a systematic POM approach is a promising way to achieve this goal. We found that alternative formulations or parameterizations of an individual demographic process could significantly improve the model performance under specific scenarios. However, such model improvements were not consistent across all scenarios, and while, for instance, short-term projections improved, long-term projections were worse than in the original model. In contrast, the simultaneous consideration of alternative formulations for *all* demographic processes and a benchmarking against the *full* range of data sets in a POM approach resulted in consistently increased model performance. This indicates that to improve the generality and robustness of forest models, focusing on individual aspects of the model may not be sufficient due to complex within-model interactions and feedback effects.

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THE CUTTING EDGE IN FOREST MEASUREMENTS AND MODELS

KEYNOTE: THE CUTTING EDGE IN PROCESS-BASED AND STATISTICAL APPROACHES

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Forest management objectives are changing rapidly as new demands are being placed on forest-based ecosystem services. In addition to wood production, we need to manage our forests for climate change mitigation and biodiversity conservation as well as adapt the management to increasing risks of damage caused by environmental change, to balance our environmental goals with an increasing demand of wood material for bioenergy and fossil material substitution. These goals together with environmental change are challenging our ways of forest modelling, creating a deepening quest to base our models on process understanding. At the same time, the models should also be able to run with available data and produce projections that are quantitatively reliable.

These expanding objectives have stimulated a convergence between forest growth and forest ecosystem models. While growth models are being extended to cover e.g. carbon sequestration and biodiversity, forest management impacts are being incorporated into ecosystem models, e.g. in global vegetation models. However, as the objectives and requirements for models are widening in scope, on the other hand, a lot of new detailed results are becoming available concerning the physiological processes of tree growth. An important challenge for future modelling work is to reconcile these apparently opposing trends, to utilise the detailed process knowledge and apply it in larger-scale, more comprehensive models. We need clever modelling that can simplify the essential and to combine multiple scales. A promising trend in this respect is provided by eco-evolutionary modelling, where the theory of evolution is put to use to find links that balance structure with function and different material fluxes with one other.

An important trend for model development and application is that more data from variable sources are becoming available for both model development, calibration and application. Many traditional data sources are becoming more openly accessible, and at the same time, there is an increasing flow of new types of data, including remote sensing, terrestrial laser scanning as well as more detailed process information from physiological measurements. If combined with efficient data-model fusion, these new data sources open up a range of new possibilities for process-based parameter estimation. Examples using inverse methods, especially Bayesian inference, are already emerging.

This presentation will introduce evidence of these new trends in forest modelling and highlight them with examples from the recent literature.

KEYNOTE: LEVERAGING BIG DATA AND NEW TECHNOLOGY IN FOREST INVENTORY AND MODELS: MOVING FROM DESCRIPTION TO UNDERSTANDING

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We are surrounded by the technology of data gathering. Even as you read this abstract, someone - Google, Apple, Microsoft - is collecting data on you. While our technology has not gotten quite so invasive with trees, we still have huge sources of data that were only imaginable a few years ago. Whether it is high density airborne or terrestrial LiDAR scans, or assemblages of growth and yield data for eastern North America, big data are a part of the forest inventory and modelling scene. Big data techniques, such as neural networks and random Forest imputation, are widely used in forest inventory analyses and growth and yield. The so called "nonparametric" techniques are the new paradigm in big data analyses. Traditional statistically-driven growth and yield models are still common, and other, more robust, modelling techniques such as copulas, have a small, but growing, base of scientists using these techniques to understand the complexities of the abiotic and biotic interactions that drive the productivity and yields of forests. As scientists, I hold that our role is to generate new understanding – new knowledge - of the systems we are modelling, not just new, better predictions. Understanding how to harness these data mining approaches to efficiently analyse these big data to produce new knowledge rather than new predictions is one of the challenges facing forest biometrics today. In this paper, I will use a few case studies to illustrate how we might approach this task moving into the future.

ASSESSING COMPETITION IN MULTI-SPECIES STANDS

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Introduction

Despite a growing interest in mixed-species plantings, we still lack a generic way to design beneficial mixtures and to make efficient prognoses of their performance. Good progress has been made with pairwise mixtures, but few publications deal with rich mixtures in generic ways. Nonetheless, insights from analyses of pairwise experiments suggest that pairwise analyses of rich mixtures might offer useful insights.

Materials and methods

A planting of 16 diverse species, replicated in 25 randomized blocks, was used to gain insights into species performance. The trial was established in 1991, and has been measured regularly for 25 years, during which time competition and mortality trends have become evident. Hegyi indices were computed for each tree for each measurement interval. In addition to the conventional Hegyi index summing all competitors, partial indices were computed for each species group. Figure 1 illustrates the raw data and simple linear regressions fitted to these pairs of inter-specific competition and diameter increment of the subject tree.

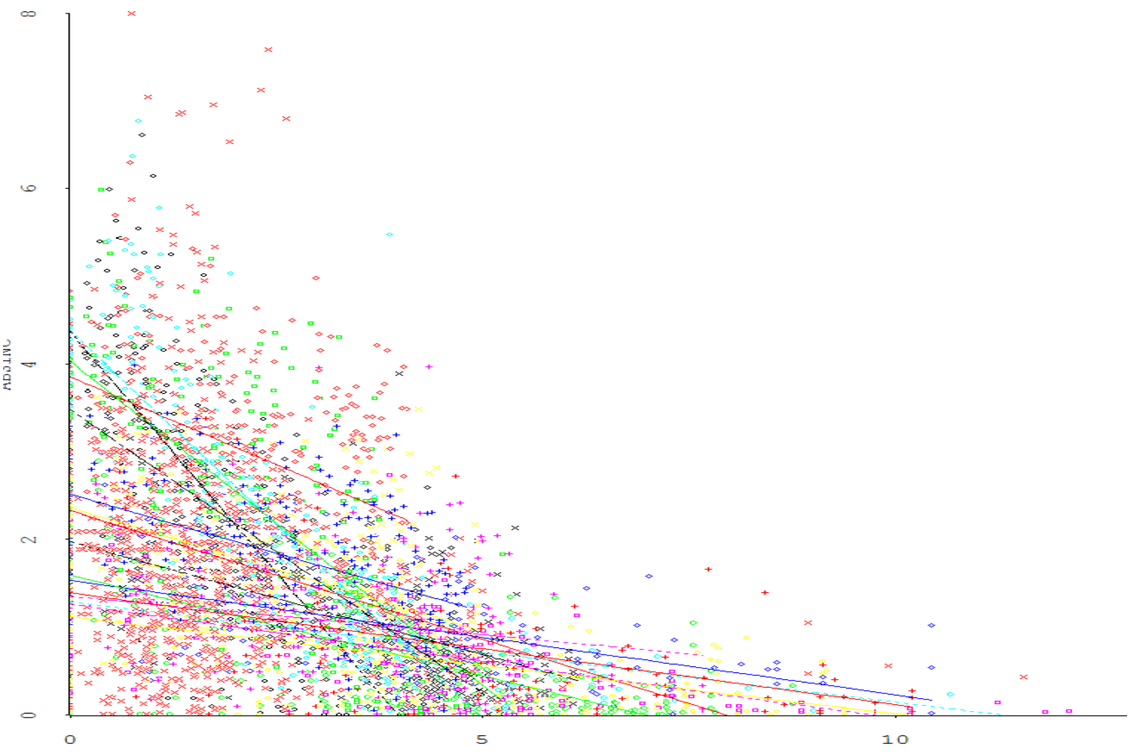

Figure 1: Growth rates of individual species and their species-specific competition.

Results

Figure 1 illustrates averages the competition across all non-conspecific pairs; further analysis drew on pairwise comparison of competing species which is more difficult to illustrate. Figure 1 reveals a wide spectrum of gradients that correlates roughly with the successional status of species (i.e., light-demanding versus shade-tolerant). These trends emerge more clearly in pairwise analyses, and range from facilitation to strong competitors, and the observed trends of all 16species align with independent prior observations of successional status. This correlation suggests the possibility to calibrate species interactions from empirical trials, and the ability to predict responses without trials for species of known silvics.

Conclusions

This trial of 16 species indicates a spectrum of species interaction responses and suggests that the spectrum is closely aligned with the successional status of the species. If this alignment is confirmed for other species and other trials, it would suggest a way to calibrate species interactions for simulation models, and to predict responses of species with known silvics but for which no trials are available for analysis.

HYBRIDIZING THE 3PG AND GLOB-TREE MODELS TO EXPAND THE 3PG OUTPUT WITH INDIVIDUAL TREE INFORMATION

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Introduction

Growth and yield models implemented in forest simulators appropriate for different spatial scales are available in Portugal for the most important forest species (maritime pine, eucalyptus and cork oak). However, the global change environment, namely climate change, gave impetus to an increasing use of process-based models. Such models, integrating the main physical, biogeochemical and physiological processes involved in forest growth and development, give a mechanistic description of the interactions between the living plants and their environment and are able to assess the energy balance and the cycling of water, carbon and nutrients within a given ecosystem. Practical problems with this type of models are the need for very detailed input on climate and soil characteristics and the lack of some of the output required for management decisions. For instance, high-resolution information on stand structure – not available in most process-based models - is essential to assess wood quality or harvesting procedures and costs. At present, it is not possible to find a unique model that does fully meet the requirements for evaluating the sustainability of multi-functional forest management. One major challenge is to combine the use of two models – a process-based and a growth and yield model – so that practitioners can take advantage of strengths of both model types. This presentation describes and evaluates a method used to improve and enrich the output provided by the 3PG model (Landsberg and Waring, 1997) for management, namely to provide individual tree information which may be needed in some applications.

Materials and methods

The 3PG model is structured in five sub-models (Sands and Landsberg, 2002) that describe 1) assimilation of carbohydrates, 2) distribution of biomass between foliage, roots and stems, 3) soil water balance, 4) determination of stem number and 5) conversion of biomass values into variables of interest to forest managers. This last module provides the information that is available from traditional empirical forest modules. Of course that current forest management take advantage of 3PG for applications that are not possible with traditional forest growth and yield models, such as the study of the impact of climate change, the study of potential productivity or the impact of intensive silviculture (irrigation and/or fertilization), therefore naming the last module as information for management is too reductive, maybe it can be named as the “calculation module” as opposed to the remaining modules that are “growth modules”. In the original 3PG, this module includes three sub-models: stand density (N), basal area (G) and volume under bark (Vu). Tomé *et al.* (2004) proposed the improvement of G and Vu estimates by using stand level density dependent allometric relationships with aboveground and woody biomass, respectively. A density dependent allometric relationship with woody biomass was also developed to predict dominant height. In the same work, Tomé *et al.* (2004) proposed a methodology to provide tree information over time using an individual tree diameter increment model of the potential X modifier type by noting that the potential growth in tree basal area (i_{gpot}) can be obtained from the stand basal area growth (i_G):

$$i_{gi} = i_{gpot}\ \text{modifier}(g_i)$$

$$i_G = \sum_{i=1}^{n} i_{gi} = \sum_{i=1}^{n} i_{gpot}\ \text{modifier}(g_i) \quad \Rightarrow \quad i_{gpot} = \frac{i_G}{\sum_{i=1}^{n} \text{modifier}(g_i)}$$

Where igi is the diameter growth of tree i; gi is basal area of tree i; modifier is a function that varies between 0 and 1 depending on the tree competitive status (evaluated by distance dependent or distance independent competition indices); and n is the number of trees.

In this presentation, the methodology presented by Tomé *et al.* (2004) is applied using the dbh increment equation from the GLOB-tree model (Soares and Tomé 2003) and evaluated to produce individual tree information along with the 3PG projections. This methodology was applied to a set of 125 permanent plots representative of 5 climatic regions and different site qualities as well as to data from 3 spacing trials. Bias and precision of the stand volume (total and merchantable) and biomass (total and per tree component) were analysed with the usual validation procedures (e.g. Burkhart and Tomé, 2012). The validation results were compared with those obtained from the simulation of the diameter distribution with a Johnson's-SB probability density function (Mateus and Tomé, 2011)

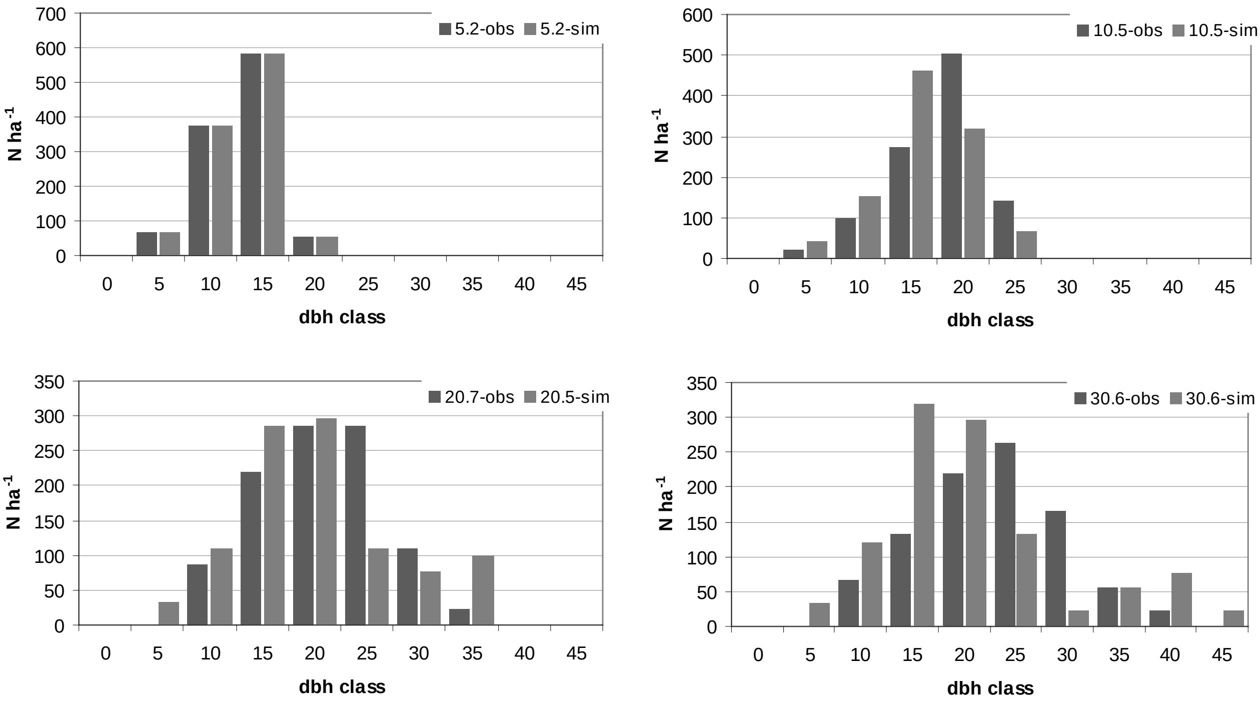

Figure 1: Observed (obs) and simulated (sim) diameter distributions of a* Eucalyptus *plot at ages 5.2, 10.5, 20.7 and 30.6.

Results

Preliminary results show that the individual tree information predicted with the Tomé et al. (2004) method provides good estimates of stand volume and biomass and that the method is able to reproduce the evolution of diameter distributions (Figure 1)

Conclusions

The preliminary results suggest that the Tomé et al. (2004) methodology is promising to enrich the 3PG output with individual tree information, allowing the calculation of merchantable volumes and other variables that require tree information. The study is still ongoing but we expect to have, at the conference, nice results to show, including the comparison with the estimates obtained with the diameter distribution simulation.

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LEAF AREA INDEX THRESHOLD FOR OBTAINING AN EXPECTED WATER YIELD FROM PLANTATIONS: A NEW SILVICULTURAL DECISSION VARIABLE?

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Introduction

Intensive forest management of radiata pine plantations has been focused on maximizing revenue, together with increasing stem volume production and wood quality attributes (Mead, 2013). Nevertheless, increasing drought, in addition to emerging conflicts with neighbour communities regarding water use in the watersheds, have opened the discussion about the sustainability of forest plantations, with emphasis in the general water balance (Andersson *et al.,* 2016). This is particularly true in the context of the predicted lower rainfall and increasing temperatures expected during this century in many regions of Chile under future climate scenarios (Cabré, Solman and Núñez, 2016).

Based on that, we propose to explore the inclusion of a new decision variable in the planning of silvicultural regimes for radiata pine (*Pinus radiata* D. Don) forests planted for timber production. This alternative variable is the threshold leaf are index (LAI) needed to attain a desirable water yield (Osem and O'Hara, 2016).LAI is a key stand attribute used for modelling forest growth in several forests models, like 3-PG (Physiological Processes Predicting Growth), expressing the amount of intercepted radiation and transpiring surface, thus being directly related to water use, photosynthesis and forest productivity (Landsberg and Waring, 1997).

In this study, we tested a new approach of stand density management, based on defining a threshold LAI that should be maintained along the lifespan of the stand, in order to provide an expected minimum water yield (WY), i.e. water not used by the plantation and therefore available for the rest of the hydrological system. We parameterized and validated the model for radiata pine plantations growing in Chile and tested the use of LAI in terms of water yield and volume production.

Materials and methods

The 3-PG model was parametrized for radiata pine plantations using the approach proposed by Gonzalez-Benecke *et al.*(2014 and 2015), including a new module that allows for thinning based on threshold upper and residual LAI. Thirty site conditions in Chile were selected, including different soils (from a wide range of textures and water holding capacity) and climate, ranging from 339 to 2154 mm year^{-1}of rainfall, and 799 to 1221 mm year^{-1}of water deficit (WD)[WD=PET-ET; mm year^{-1}; PET: Potential Evapotranspiration, ET: Actual Evapotranspiration].First, a whole rotation period of a standard stand of 1250 trees ha^{-1} was modelled using the newly parameterized 3-PG model, and yearly LAI, water yield and stem volume yield were computed. Then, some critical or desired values of water yield (40%, 60% and 80% of total annual rainfall) were tested, and the mean LAI that can support this water yield were obtained. The model was modified allowing for thinning based on LAI, so the user can define a threshold LAI (upper level that triggers thinning) and a residual LAI (lower level after thinning). Finally, thinning schedules per site condition were designed so as to maintain the critical LAI and were analysed in terms of stem volume yield.

Results

In Figure 1a the relationship between mean annual projected LAI ($m^2\ m^{-2}$) and relative water yield (WYr) [WYr= (Rainfall – ET)/Rainfall; mm $year^{-1}$] on sites with different Potential Evapotranspiration (PET) are presented. Only low LAI (lower than 1.5 $m^2\ m^{-2}$) can support a positive externality of high water yields over 0.8. Figure 1b shows the relationship between WYr and stand volume over bark (VOB; $m^3\ ha^{-1}$) at age 22 years (logarithmic scale). There is no relationship between WYr and VOB for WY<0.65 (ln (WYr) =-0.43 in Figure 1b). As WYr increased over 0.65, VOB yield decreased sharply. Figures 1c, 1d and 1e show the relationship between Water Deficit and critical LAI for a Water Yield of 40%, 60% and 80%. Validation not presented here.

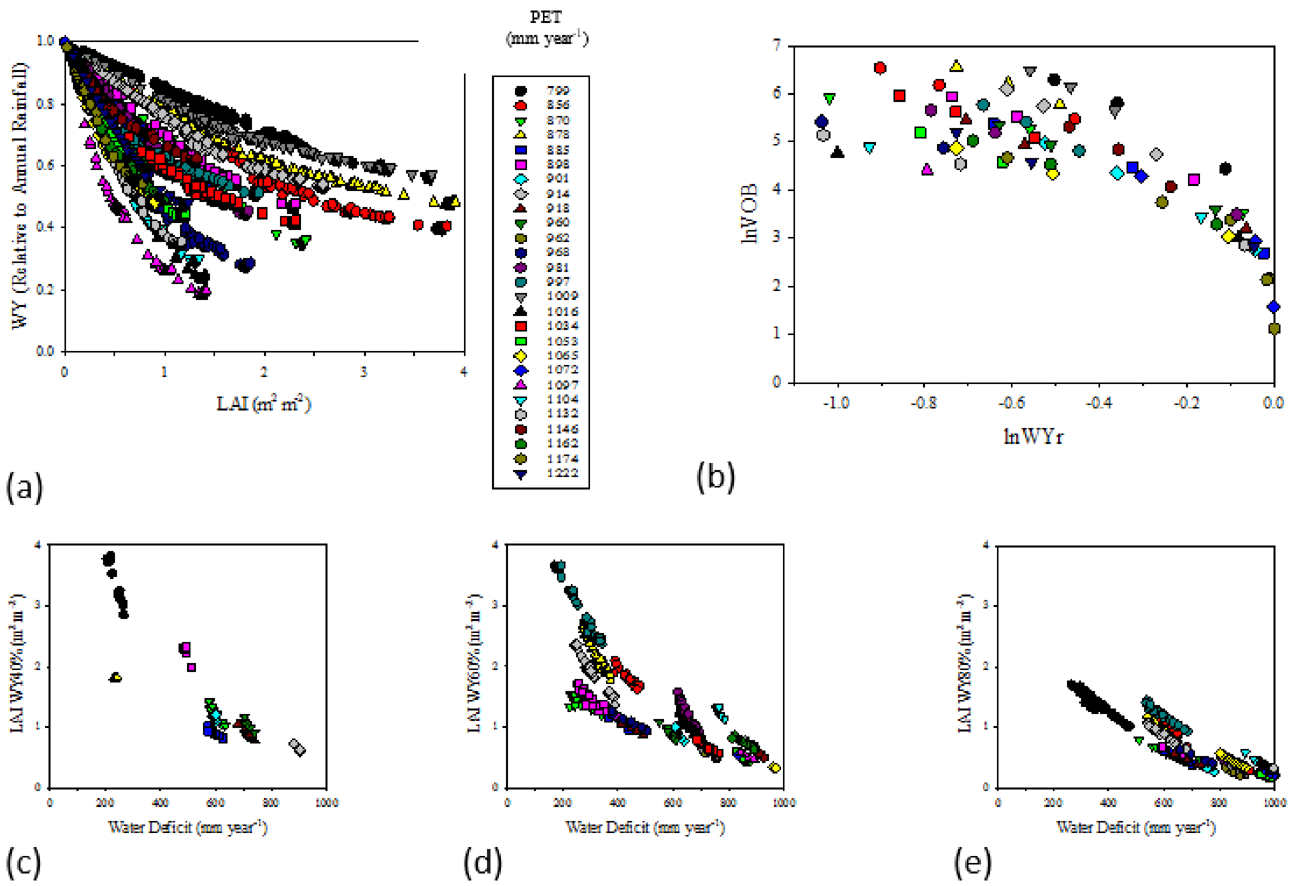

Figure 1: Relationships between (a) mean yearly LAI and Water Yield, (b) relative Water Yield (WYr) and stand volume over bark (VOB) at age 22 years (logarithmic scale), Water Deficit and critical LAI for a Water Yield of (c) 40%, (d) 60% and (e) 80%on sites with different Potential Evapotranspiration (PET, mm year^{-1}).

Conclusions

Water, as a vital resource should be considered in future management as has been already proposed by different researchers (Baskent and Keleş, 2009). Nevertheless, further calibrations and validations, together with researchers related to the hydrological sciences would be necessary. Desired or objective water yield is a matter of further research and will depend on the hydrological basin and the demand of water by different stakeholder. It is difficult to properly satisfy both objectives, more water yield by mean of management based on LAI, and high productive plantations in terms of volume production. But we must begin to test also the future of forest management schedules in those terms, given the coming climate change scenarios with less rainfall, the rising of fire risks in highly dense plantations, and the complains of local people regarding water availability in the basins occupied by forest plantations.

We parameterized and validated the 3-PG model for radiata pine plantations. We included a new thinning module that allows the user to simulate the effects of reductions in tree stocking (and therefore LAI), by defining threshold LAI limits. We determined the values of LAI that allows to obtain a desirable water yield based on stand water deficit. Finally, thinning schedules per site condition were designed so as to maintain the critical LAI and were analysed in terms of stem volume yield.

Acknowledgment:

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HIGH DENSITY WAVEFORM LIDAR – ACQUISITION AND PROCESSING METHODS FOR FOREST STAND PARAMETERS DERIVATION

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Introduction

Laser scanning (LiDAR) is a surveying technique using short laser pulses to accurately measure distances to remote objects (Shan *et al.*, 2009). By means of a laser source equipped with a high pulse repetition rate and an optical deflector, a laser scanner samples the visible surface of an object, thus creating a dense 3-dimensional point cloud representing the surveyed objects (Vosselman *et al.*, 2010). For example, a point cloud representing a digital copy of a tree can be used to derive various forestry parameters, such as tree height, crown diameter, overlap factor or even diameter at breast height (DBH). This paper describes the latest developments in laser scanning technology, discusses the various acquisition methods and provides some recent results of laser scanning projects for forestry applications.

Materials and methods

Waveform LiDAR: the laser scanning systems featured in this paper are all based on the time-of-flight measurement principle. Such systems measure the time difference between an outgoing laser pulse and a received echo signal resulting from the reflection on a solid object. Especially when measuring vegetation multiple echo signals overlay to complex waveforms which require algorithms like a Gaussian decomposition (Wagner *et al.*, 2010) to extract the individual echoes to calculate the respective distances. We will discuss and compare the methods of online waveform processing (OWP, Pfennigbauer *et al.*, 2010) implemented in the Lidar systems and post-processing in software. To this end very recent developments of combining online waveform processing with full waveform decomposition for those waveforms where the pulse shape deviation from OWP exceeds a certain threshold ("smart waveforms") will be presented.

Acquisition platform: Lidar for vegetation mapping can be mounted on various platforms. Nowadays mostly airborne platforms are used for extended surveying campaigns. Besides fixed wing aircrafts, recent developments in the Lidar sensor technology allow for use of light aircrafts and even unmanned aircrafts. Under certain environmental conditions ground based setups may be considered an alternative, as well.

Figure 1: LiDAR Acquisition Platforms: Fixed Wing Aircraft, Unmanned Aircraft, Static Tripod

Point cloud classification: the result of a LiDAR survey is the 3-dimensional point cloud. To derive any forestry parameters, it is mandatory to classify the points depicting ground, vegetation and non-vegetation objects. The ground classification algorithm classifies ground points in a point cloud by progressive TIN densification (Axelsson, 2000). The insertion of points to the TIN is controlled by the minimum edge length as well as maximum angle and distance parameters. Vegetation is sliced into three vegetation height levels based on a calculated height above ground attribute.

From the classified airborne laser scanning data single trees can be extracted via a rasterized crown height model. Algorithms are applied to derive segments representing treetops of single trees as well as tree trunk positions. From these crown segments various metrics are calculated like the crown area, radius and shape ratio to remove small or elongated segments.

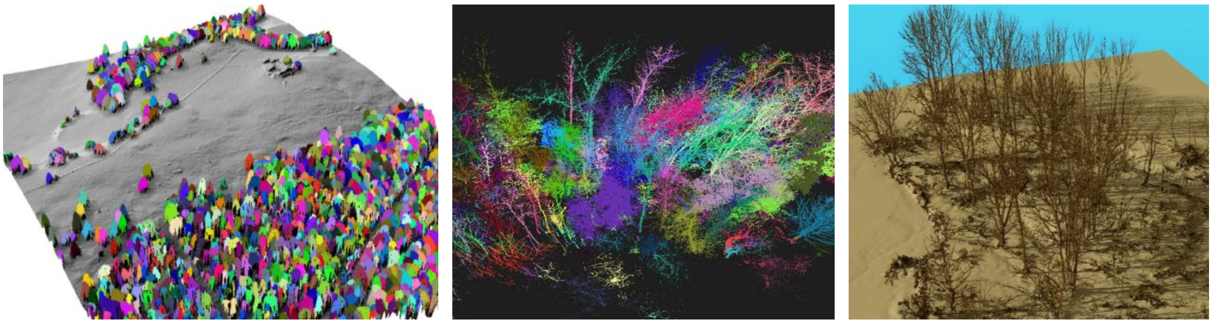
From terrestrial or UAV based laser scanning point clouds the algorithms also start from a ground, non-ground classification in combination with height above ground information for each point. Tree trunk detection is performed by height level slicing at breast height and the creation of centred tree trunks at ground level. This allows to segment the non-ground point cloud by applying a Dijkstra region growing from the tree trunks (Livny *et al.*, 2010; Bremer *et al.*, 2013). Besides performing the point cloud segmentation two 3D models from the segmentation results are generated as 3D shapefiles: a skeletonized line shapefile and a 3D pipe model as volumetric tree model (e.g. for urban tree cadastres).

Results

The segmentation of ALS based crown height model allows the calculation of tree density to estimate e.g., their protection function. In addition, for every crown segment its area, height and average diameter can be derived as shapefile.

From terrestrial laser scanning data detailed parameters per tree can be generated via a bottom up approach starting from the reconstructed tree trunks. The diameter at breast height can be measured and attributes on branching hierarchy and stem volume are calculated.

Tree models are useful as 3D results for visualisation in urban planning, either as volumetric models or as linear skeleton models in urban street environments. The branching index is also useful in urban environments to further distinguish between trees, traffic signs and lights.



a) b) c)

Figure 2: a) Segmented crowns from airborne laser scanning data b) Single tree delineation from terrestrial laser scanning data c) Volumetric 3D pipe model from UAV based laser scanning data

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MODELING THE SPATIAL STRUCTURE OF WHITE SPRUCE PLANTATIONS

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The spatial distribution of trees has important implications for forest management (Batista & Maguire 1998, Pommerening 2006), even if it is seldom used. It is very useful to understand complex forest structures (Pretzsch, 1997) and to simulate forest dynamics by integrating interactions between trees (Genet et al., 2014). In addition, spatialized data may, under certain circumstances, improve the accuracy of some models (growth, quality, regeneration, survival rate, etc.) (Weiskittel et al., 2011). However, measuring the coordinates of all trees in a stand can be long and costly. The development of LiDAR technology improves the speed and accuracy of these measurements (Martin Ducup et al., 2016). The objective of this study was to analyse the spatial patterns of trees and to develop a simulator able to reproduce the spatial structure of the forest by attributing coordinates to non-spatial inventory data.

Materials and methods

- **Data acquisition**

Fifty-nine plots were sampled in four white spruce plantations in eastern Quebec, Canada (33 plots of 450m² and 26 of 1000m²). An experimental design was established in which five commercial thinning treatments were randomly assigned to each plot (Gagné et al. 2016). The plots were scanned with a Focus3D Faro, a terrestrial laser scanner, to cover the entire surface and minimize occlusion. From the three-dimensional point cloud obtained, the coordinates of all the trees was extracted. Tree species was determined during the forest inventory of the plots. White spruce (*Picea glauca*) (WS) and balsam fir (*Abies balsamea*) (BF) were considered separately and the hardwoods with commercial interest were grouped together (VH).

- **Spatial Analyses**

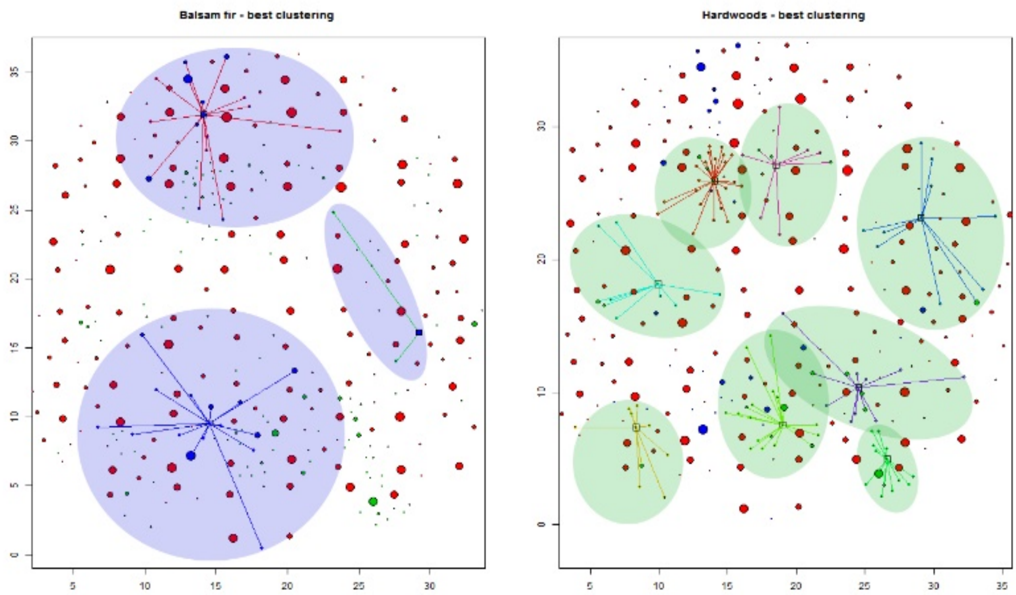

Figure 1: Example of species aggregation in a plot

At the plot level, the spatial distribution was studied with the Clark-Evans Aggregation Index (CEI). For species that tend to cluster, the number of groups per hectare (NbGroup) was modelled with a Poisson regression using stand characteristics (CEI, thinning treatment, tree density) and the number of trees for the studied species as predictive variables. Within these groups, the closest distance between two trees of the same species (MinDistGroup) was modeled with a Gamma regression using stand characteristics and the diameter at breast height (Dbh) of the two neighboring trees as predictive variables (Figure 1).

At the individual tree scale, the minimum distances between a tree and its two closest neighbours among all trees (MinDist1, MinDist2) were modelled with a Gamma regression using stand characteristics and the characteristics of the three neighbouring trees (species, Dbh) as predictive variables.

Results

- **Spatial Analyses**

At the plot scale, we observed that WS had a regular distribution (CEI > 1) whereas BF and VH tended to be more aggregated (CEI < 1). The root-mean-square error (RMSE) of NbGroup model was 0.16 (R^2 = 0.41), 3.22 (R^2 = 0.19) and 2.39 (R^2 = 0.28) for WS, BF and VH, respectively. An RMSE of 0.48 (R^2 = 0.38) and 0.56 (R^2 = 0.32) were obtained for MinDist1 and MinDist2. Statistically significant differences between the different sylvicultural treatments were also observed.

- **Simulation**

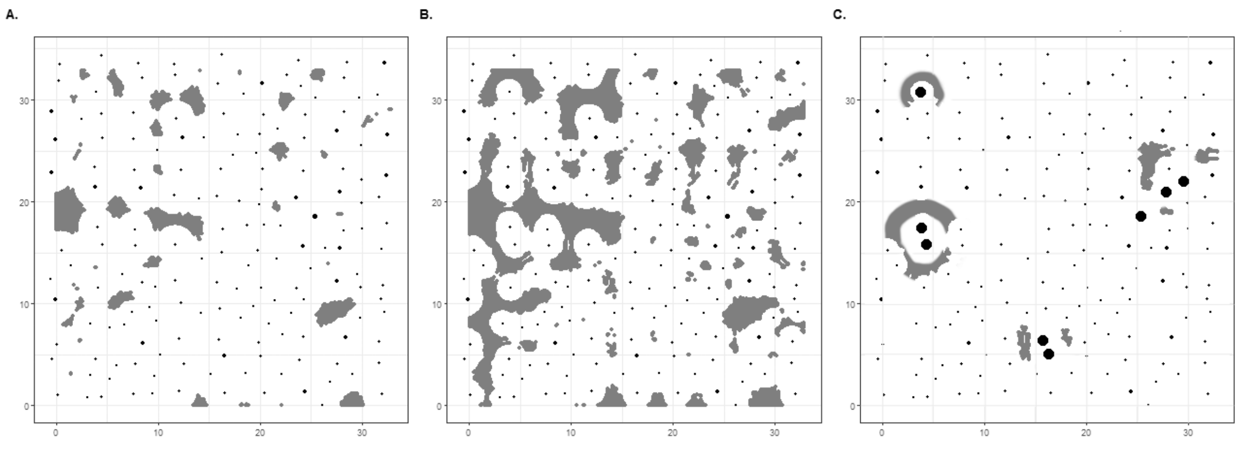

Figure 2: Potential valid positions for A) a WS tree with a Dbh of 25 cm, B) a WS tree with a Dbh of 9 cm and C) a VH tree with Dbh of 9 cm. The dark grey areas correspond to possible valid coordinates to positon the tree; the black dots are the position of trees already positioned.

In order to attribute spatial coordinates to a non-spatialized inventory, the tree list is first sorted by Dbh. The first tree is randomly placed within the plot boundaries. For the other trees, a random position is generated within the plot, and the distance from the two nearest trees (d1 and d2, or if the second tree, only d1) are compared to the minimum distances (MinDist1 and MinDist2). If d1 is greater than MinDist1 and d2 is greater than MinDist2, the position is considered acceptable. Otherwise, a new random position is tested. For species that tend to cluster (i.e. BF and VH), the area where to randomly chose the location of the tree is restricted by the CEI, which depends on the tree species and its size (Figure 2). The simulated CEI was compared to the observed CEI within the calibration plots, with very little differences observed.

Conclusions

In most inventories, the coordinates of the trees are not available. Under certain circumstances, this information is necessary as, for example, the input into certain growth simulators. The 'spatializer' presented here accounts for the attractive behaviours between trees of the same species (NgGroup, MinDistGroup) and repulsive behaviours between trees too close to each other (MinDist1, MinDist2). The spatialisation model has been added to the PlantaBSL growth simulator programmed in Capsis. It is a tree growth simulator for plantations in Quebec where many sylvicultural treatments can be tested and evaluated.

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USING AIRBORNE LASER SCANNING AND DIGITAL AERIAL PHOTOGRAMMETRY TO ENHANCE FOREST GROWTH AND YIELD PREDICTIONS

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Introduction

Sustainable forest management requires accurate information on both the current stock, and future growth and yield. This information, collected during forest inventories, is crucial for evaluating current and projected conditions of a forest, as well as being critical for assessing the consequences of management decisions. Predictions of stand growth and yield are often performed at the stand level, with inputs provided by conventional forest inventory data derived from air photo interpretation and ground samples. Recently there has been a marked increase in the use of airborne laser scanning (ALS), digital aerial photogrammetry (DAP) data and an area-based approach (ABA) to derive key forest stand attributes to augment these conventional inventory data; however, a clear link from these current ALS and DAP estimates to estimates of future growth and yield has not been extensively studied. Herein we demonstrate a novel approach to utilizing ALS- and DAP-derived forest stand attributes to determine future growth and yield of key attributes at 20 m grid cell level. We also discuss how the more detailed projections of forest attributes can provide valuable information on wood characteristics and timber quality.

Materials and method

The study area was located near the town of Slave Lake, Alberta, Canada, and was approximately 700,000 ha in size. ALS and DAP point cloud data was acquired for the study area in 2007 and 2015, respectively. Permanent sample plot (PSP) data were used to create ABA predictive models of four selected stand attributes, including top height (H), basal area (BA), total volume (V), and number of trees per hectare (N), using ordinary least squares regression. Because the PSPs were measured twice, and corresponded to ALS (time 1, T1) and DAP (time 2, T2) data acquisitions, two predictive models were developed for each selected attribute, using ALS- and DAP-based predictors, respectively. These models were then used to generate wall-to-wall prediction rasters of each attribute with 20 m pixel size. We utilized an existing, stand-level forest growth model (GYPSY) to generate a comprehensive database of yield curves (templates) for all possible combinations of dominant species, site index, age, and canopy cover. Then, for each of the forest stand attributes, we demonstrate an approach to find the most appropriate matching yield curves from all possible templates, and subsequently demonstrate the projection of these three attributes at 80 years of age. The yield curve matching approach assigned a best possible yield curve to each of the ground plots. The selection process to assign the best possible yield curve that matched stand attributes was based either on observations recorded at T1 (approach 1), or based on the combination of observations at both T1 and T2 (approach 2). First, candidate curves were selected from the database, based on the minimal difference between the stand attribute and a value of a yield curve.

Since four ABA-predicted stand attributes were used, this resulted in four candidate curves in approach 1 and eight in approach 2. The final yield curve was derived by calculating a weighted mean of the candidate curves, with the percent of explained variance in the ABA model used as a weight. This allowed assigning more weight to the attributes that were modeled with greater accuracy and increased the reliability of the final curve. Curve matching was performed for all 20 x 20 m cells.

Results

Comparisons of cell-level projections to conventional stand-level projections resulted in relative mean differences of 13.4% (dominant height), 18.8% (quadratic mean diameter), and 18.6% (whole stem volume). The respective relative root mean squared deviation values were: 31.1%, 19.8%, and 21.8%. Differences were driven mostly by stand-level age and site index values that were used in the cell-based modelling, which were derived from conventional stand-level forest inventory data. We found that the accuracy of cell-level yield curve assignment increased with increasing distance from the stand boundary, which was used to refine stand-level summaries—an important consideration for stand-based forest management.

Conclusions

The novel contribution of this study is in the application of growth and yield models at the cell level, combined with the use of ALS-derived attributes to optimize yield curve selection via template matching. The benefits of the approach include improved within-stand spatial detail, optimization of yield curve selection, and the capacity to incorporate spatial uncertainty into stand-level estimates of projected attributes of interest. The additional sub-stand level of detail of the projected forest stand attributes provides also opportunities to improve predictions of wood-related characteristics, and support decision-makers with more precise information on wood quality.

USING 3-DIMENSIONAL POINT CLOUDS TO IMPROVE CHARACTERIZATIONS OF TREE STEMS ACROSS SCALES IN BOREAL MIXEDWOOD FOREST STANDS

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Introduction

An essential component of understanding forested landscapes is undertaking inventories of the resource at varying spatial and temporal scales. The extent and complexity of boreal forests can make undertaking inventories difficult – particularly across the diverse species, age gradients and disturbance regimes that exist in mixed wood stands, one of the most common ecosystem types in Canada's boreal forest (Drapeau*et al.*, 2000). While components of a forest inventory can include species mixtures or age distributions, individual tree dimensions are critical measurements which provide a basis for the remainder of a forest inventory and inform wood quality parameters. Tree location or detection, measurements of the diameter at breast height (DBH), height, taper and branching structure are useful in determining tree characteristics. When used in tandem, these attributes are fundamental to a variety of other measurements, such as tree volume or by group measures such as a stem size distribution (SSD), which represents the relative frequency of tree sizes in a given area (Taubert *et al*., 2013). SSDs can contribute to the assessment of a tree's merchantability or utilization for harvest (Landsberg *et al.,* 2005).

Complete characterization of a forest requires the estimation or measurement of trees in all stands in the area of interest. In this capacity, traditional ground-based inventory methods are spatially constrained, expensive, and time consuming. The advancement of remote sensing technologies and development of associated methodologies has made it easier to survey forest attributes quickly and effectively. Broad-scale estimation requires operation from the air, while detailed plot- and tree-based estimates typically come from ground-based sensors. The most common sensor for large scale forest inventories due to its ability to accurately and continuously characterize large areas is Airborne Laser Scanning, or ALS (Hudak *et al.*, 2009). ALS point clouds are used to generate descriptive metrics characterizing height, volume, and biomass on larger scales (Næsset, 2002), as well as finer scale descriptions such as crown dimensions, and vertical and horizontal canopy structure (Coops *et al.*, 2007). A developing technology applied to finer scales of inventory is digital terrestrial photogrammetry (DTP), which is an inexpensive alternative to ground-based laser scanning. DTP uses images to create a detailed point cloud which can be used to characterize stem attributes and used as inputs for harvesting and wood quality assessment. Combined, ALS and DTP can be used to characterize stems at multiple scales, from measuring their individual characteristics to assessing patterns of their distribution across the landscape. In this paper we describe new methods for estimating individual stem attributes and modify existing techniques in order to assess tree attributes from tree to stand scales across a boreal mixed wood forest.

Materials and methods

The study area is an actively managed boreal mixed wood forest near Lesser Slave Lake in Alberta, Canada. The area is approximately 700,000 ha in size with 10 common species including white spruce (*Picea glauca)*, black spruce (*Picea mariana*), trembling aspen (*Populus tremuloides*), and lodgepole pine (*Pinus contorta*) as the most dominant. Measurements of 71 Permanent Sample Plots (PSPs) in the study area were taken between 2006 and 2007, and again in2016 and 2018.

First, at stand scale, we used ALS to characterize SSD on simple (unimodal) and complex (bimodal) structural types. We applied the bimodality coefficient to 71 PSPs and identified 23 (32%) as bimodal and 48 as unimodal with respect to SSD.Various stand characteristics, measured on plots and predicted using ALS, were assessed for their ability to identify the plots as either unimodal or bimodal. Once the best ALS-based metric for identification was determined, it was used to categorize plots for estimation of SSD parameters by ALS – a Weibull model for unimodal stands and a Finite Mixture Model (FMM) for bimodal stands. Field-based SSD on classified plots were used as response data for prediction with a suite of ALS metrics. Finally, the accuracy of the resulting curves was assessed with an Error Index (EI; Reynolds *et al.*, 1988).

Next, on the tree scale, we evaluated the accuracy of DTP point clouds in characterizing stem measurements, such as DBH, location, and upper stem diameter. We used two RICOH THETA S cameras, each capable of capturing 360˚ images (Ricoh Company Ltd., 2017) mounted on a telescoping pole capable of taking images from 1.3m to 5m high. The images were processed into point clouds and individual stems were filtered out. DTP-based estimates of DBH and upper stem diameter were compared to ground measurements and overall accuracies were related to acquisition conditions such as light intensity, stem density, and understory to determine how the accuracies of point clouds were influenced by these conditions.

Results

We found that the variance of ALS return heights was the best metric for differentiating between unimodal and bimodal stands, with a classification accuracy of 77%. Parameters of both the Weibull and FMM distributions were accurately predicted (r^2 ~ .5, RMSE ~ 30%), and that differentiating for modality prior to estimating SSD improved the accuracy of estimates (EI of 49.13 with differentiation versus 51.31 without differentiation).The ground-measured variables best able to differentiate bimodal distributions were those relating to tree sizes, such as the standard deviation of heights and DBHs. Preliminary results indicate the success of DTP for modelling individual stem attributes and suggest that accurate estimates of DBH, height, and taper can be made from DTP point clouds in mixed wood forest stands.

Conclusions

The difference in structures and stem forms among stands requires detailed, landscape-level information to guide the fitting and modeling process. At larger scales differentiation by ALS allowed us to fit structurally appropriate SSDs to respective stands and allowed for more robust characterizations of SSD than using a single model for the entire study area. For forest professionals who rely on both detailed tree-level measurements and stand-level information, being able to quickly and effectively characterize the forest at both scales provides crucial insights that lead to more informed localized management decisions and more accurate ecological understanding of stem attributes and stand structure in complex habitats.

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APPROACHES TO ESTIMATING DIAMETER DISTRIBUTIONS FROM TERRESTRIAL AND AIRBORNE LIDAR VIA COPULAS

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Introduction

Light Detection and Ranging (LiDAR) can create three-dimension pointclouds of forest structure and maps of ground surface. These features have been shown to be useful for quantifying forest stand parameters such as density and tree height at broad scales(Means *et al.*, 2000).

Acopula is a special class of multivariate distributions where the marginal distributions are all uniform [0,1] distributions (Genest and MacKay, 1986). The uniform marginal can be stripped from the copula and replaced with any probability distribution though a statistical process known as translation (Genest and MacKay, 1986; Nelsen, 2006). By translating into any mix of distributions (Nelsen, 2006), copulas become a flexible and powerful tool for analysing dependent processes arising from a number of different underlying factors (Genest and MacKay, 1986; Wang, 1998). While copulas have been widely applied in many fields (Genest and MacKay, 1986; Frees and Valdez, 1998; Wang, 1998; Nelsen, 2006; Yan, 2007), they have only recently been applied to modelling forest structure and dynamics(Kershaw *et al.*, 2010) and individual tree height-diameter relationships(MacPhee *et al.*, 2018).

LiDAR presents many opportunities for individual tree analyses and much work has focused on individual tree segmentation and attribute estimation (e.g., Li *et al.*, 2012). Through developing moment-based parameter recovery of Weibull distribution for predicting the parameters of the copula marginal distributions from LiDAR attributes, the copula-based diameter-height models have potential to improve individual tree attribute prediction from LiDAR data (MacPhee *et al.*, 2018).

Materials and methods

The Noonan Research Forest (NRF, N 45°59'12", W 66°25'15") located approximately 30 km northwest of Fredericton, New Brunswick, Canada, is approximately 1500 ha and is composed of a diversity of stand structures and species compositions typical of the Acadian Forest. Three 50 m by 50 m mapped plots with field DBH measurements from a black spruce stand, eastern hemlock stand, and mixed hardwood stand in NRF were used to compare with predict diameter values.

The study used LIDAR-extracted heights to estimate DBH distributions for individual trees. The impacts of three LiDAR sources (airborne leaf-on, airborne leaf-off, and terrestrial) on height distributions and four approaches for predicting diameter distributions are explored. The von Bertalanffy-Richards function is widely used as height-diameter equation because of its simplicity and flexibility (Huang et al., 1992; Kershaw *et al.*, 2008; Russell et al., 2011). To estimate the diameter distribution via LiDAR height, the standard H-D equation form is solved for DBH and fitted to the field measured data. Four approaches were used: diameter-height (D-H) prediction using non-linear least squares approach; D-H prediction using random Forest imputation; moment–based Weibull parameter recovery based on nonlinear least squares prediction of moments; and moment–

based Weibull parameter recovery based on random Forest imputation of moments. The moment-based methods used copula models to link D to H.

Results

The diameter distributions derived from copulas retained more of the original variation than did those derived from the direct prediction of DBH. Due to differences associated with the LiDAR-extracted heights, the H-D distributions did align very well. However, when field-measured heights were used with the D-H copulas the results were equivalent to the field data. Heights extracted from TLS point clouds as well as the associated point cloud metrics were much lower than those derived from airborne LiDAR and field measurements. A ration correction factor calculated as the ratio of the mean of the leaf-on airborne LiDAR heights and the mean TLS heights.

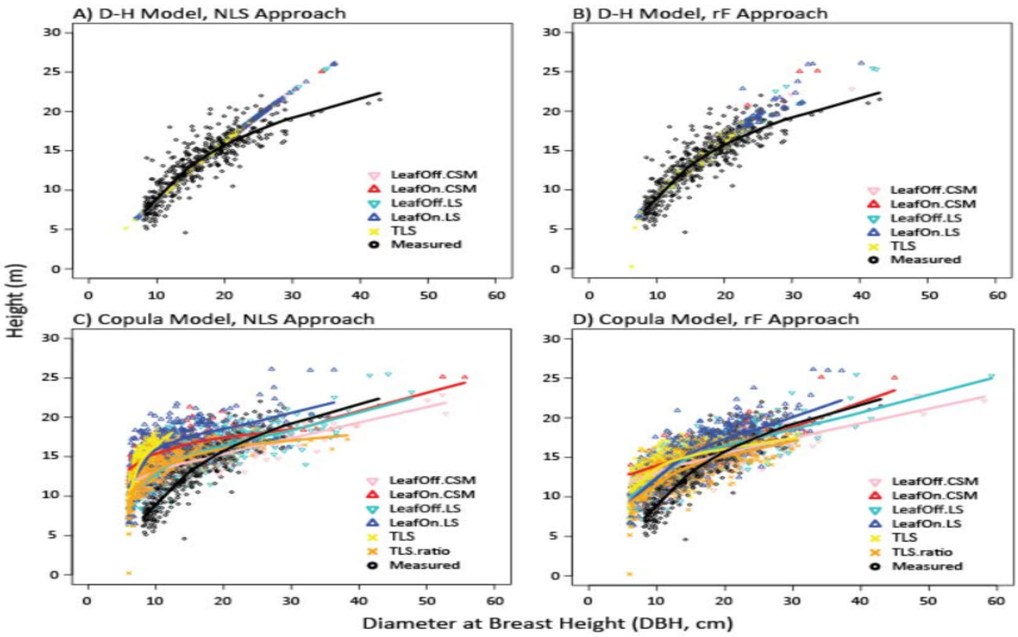

Figure 1: Comparisons between measured DBH and estimated DBH distribution for four approaches with three LiDAR sources (airborne leaf-on, LeafOn; airborne leaf-off, LeafOff; and terrestrial, TLS)

Conclusions

Extraction of heights from LiDAR that were consistent with field measured heights was challenging despite several other researchers reporting good success in this process (Sexton *et al.*, 2009; Andersen*et al.*, 2014). Although the three LiDAR height distributions are not very close to the measured height distribution, the diameter distributions estimated by the copula models performed very well. The diameter and height distributions can be used to estimate other attributes such as volume or carbon content and summed to obtain more precise area-based estimates.

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MODEL APPLICATION, INTEGRATION AND ACCESSIBILITY FOR FOREST MANAGEMENT, PLANNING AND PRODUCT DEVELOPMENT

KEYNOTE: FOREST GROWTH MODELLING FOR DECISION MAKING: PRACTICAL APPLICATIONS AND PERSPECTIVES

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Commercial forest production is a competitive industry. Productivity of planted forests may be strongly influenced by environmental variables. Robust forest growth models to support decision making processes are crucial for planning wood supply, and to define management options, but there are uncertainties and limitations that need to be recognised and addressed.

In order to understand these, and the current use, expectations and possible directions for model development, I prepared and applied a survey relating to the development and application of forest models that was sent to 150 people from 16 countries. There were 106 responses, mainly from people in academic and research institutes, and industry representatives who work with forest models. The replies indicated that 71% are using empirical models, 57% process-based models and 35% hybrid models. Some use more than one type of model. The 81% of respondents say that model accuracy and type of outputs are the most important aspects for model selection and more than 60% believe that data requirements and scale of application are equally important.

Despite the fact that 80% of the respondents make decisions based on model outputs, 55% indicated that the models are not fulfilling their requirements. They indicated that the most important desired model outputs are the predictions of current forest growth and potential productivity for different sites. A common concern is how to predict the effect of climate variability or change. Only 11% are highly confident that the models they use are able to accurately predict growth under such conditions, 64% have medium and 21% low confidence. The respondents indicated that they want to see the models be able to predict the effects of management practices (57%), pest and diseases (54%), fertilisation (41%), climate change (57%), and performance of different species (47%), and to quantify uncertainties (54%). In terms of future directions they indicated a need for better integration of modelling platforms with existing forest systems (75%), remotely sensed data (74%), other systems such as logistics of harvesting and wood supply, ecosystem services and economic aspects (52%), and with hydrological models to predict water production (42%). Future models should be more user friendly (47%), and produce outputs at multiple scales (43%).

The way forest models have been applied vary between developers, industries and regions, but overall the information produced from their application is normally analysed, and decisions are made that provide guidance on which directions and actions must be taken. Less often, industries or researchers link outcomes from forest models with an analysis of risk and uncertainty that helps understand the level of sustainability of the forest and the industry.

Empirical models are the most used category of forest model because their use is based on inventory data and for producing information of interest to estimate wood stock. Practical application of process-based models (PBM) or hybrid models has increased, with several examples now contributing to the prediction and understand of forest growth under different environmental conditions and species. This has been influenced by published parameter sets for different species, and outputs that allow the user to analyse the impact of climate variability.

An important use of PBMs is to predict potential productivity in a region, and especially in areas with no history of forest production, and without inventory data. This estimation can indicate the value of the land. It is also relevant to defining best management practices, species to be planted, stocking, spacing and the amount of fertiliser required to achieve potential productivity.

Forest growth analysis is basically a cause and effect analysis. Responses are required to simple questions such as: how much a drought could reduce growth, or what sort of management practices or genotypes are better adapted to particular conditions, what is the water use by a plantation, what are the factors limiting growth, and how much do these factors affect production?

Another area of application of PBM is related to their use in influencing the long term strategic direction of a forest company. For example, by using future climate data it is possible to simulate the likely impact of climate change on production. Such data help decision makers adopt different risk options.

More than a decade ago there were some publications predicting the future development and use of PBMs. Comparing those expectations with the actual application of PBMs it is clear that significant progress has been made, with several practical examples of implementation, but it is still not widely used as operational toll by the industry. In part, the reason for that is due to the conservative nature of the forest sector. But it is also due to the costs required to produce the necessary data, and that more complex models require a greater capability from their users. This is especially a problem when potential users have not been exposed to the potential and practical examples of model applications.

Accuracy of the outputs is probably the most important aspect with which users are concerned. This, as with empirical model platforms, will depend on the quality of the inputs. Well calibrated PBM's are able to reproduce what happens in the real world under varying or different conditions and environments, and at both spatial and plot scales. Outputs from these models are used to promote discussion amongst forester managers, learn about plantation behaviour, and to virtually test changes in practices.

Investments in process-based modelling depend on the size of the business and its objectives. The main benefits can be monthly predictions of growth, simulation of future scenarios, help to reduce effort and cost of inventory, and to understand yield gaps and water use by plantations and native forest.

It is crucial to listen to the expectations and requirements of clients and potential users. Models should be practical tools, so it is important to discuss the user's ideas and how to best implement these.

Equally important is to recognise the limitations and unknowns of models and their applications, and to avoid using models to respond to questions that they were not designed to answer. Validation of models in different contexts and environmental conditions builds trust with users. It is also important to listen to what the market is indicating, with new wood products replacing others that may create new opportunities.

Users are indicating as a priority that more user friendly interfaces able to provide quick and accurate responses are developed, that use only readily available data including the practical use of remote sensing data.

It appears likely that demand will increase for multiproduct and multiscale platforms that are able to provide values not only for wood products but also for non-wood forest products such as water, environmental services and biodiversity.

In conclusion, future forest models and their applications should aim to

- use information wisely, achieving the maximum benefit from available data;
- be user-friendly, and fully integrated with other existing forest management systems;
- convince model developers to engage potential users, and listen to and incorporate the opinions of different sectors into model development.

MODEL DEVELOPMENT AND ADOPTION IN SA FORESTRY: CHALLENGES AND SUCCESSES

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Introduction

A fundamental component of a successful forestry industry is the ability to predict and forecast stocks and flows of assets, products, and resources with reasonable precision and accuracy in a diverse and changing environment. Although achieved through use of deterministic and stochastic models at varying levels of complexity, increasing data availability provides opportunities to explore new and existing models. There are numerous examples of past and present model use that have maintained a profitable industry despite shrinking resources and a changing environment; the most effective of these remain as hidden intellectual property. The models generally serve a need to estimate and forecast supply, demand, quantity, intensity and quality of various components of forest economics, logistics, production, and risk *inter alia* along the nursery-plantation-mill-market chain. While certain models are deterministic, a majority are stochastic predictions developed through various probabilistic modelling tools that include least squares regression, machine learning, Monte Carlo simulation, geospatial statistics and so on. Model development and adoption continues to grow through technological improvements and an industry held belief in the value and potential benefits that models have for contending with increasing complexities and challenges faced by the forestry industry. Opportunities exist to develop integrated models to improve prediction of quality and quantity of fibre supply within the context of a wide range of site types and changing product requirements; and in response to climate change, and related losses through increased extent, severity, and frequency of biotic and abiotic factors. This is a discussion presents case studies of model use and non-use, and opportunities within the context of Sappi and the broader South African forestry industry to close the gap between industry need and academic advancement.

Discussion

Approximately 9% of 1.2 million ha South Africa forestry industry is re-establishment annually (FES, 2016). Choice of genotype is due to market requirement, value addition, and suitability to sites with diverse climate, topology, soils, biotic and abiotic risk factors (Smith *et al.*, 2005b; Louw *et al.*, 2011). Site x genotype matching is based on deterministic models (rules) formulated using a combination of empirical research and model-derived spatial projections of risk and economic impact. Modelling of frost and snow risk, for example, has used statistical models based on empirically derived measurements, observations, and remote sensing. These have been further developed and refined within an economic context and are continually updated to better inform genotype choices. Further development beyond site x genotype matching for tree survival, growth, and uniformity requires understanding of site and climate change effects on wood properties, pulp yield, and extractives. A site species trial planted on contrasting geologies (Tillite and Natal Group Sandstone) positioned on warm and cool aspects, and crest, mid and foot slope positions has demonstrated within-site impacts on growth, wood basic density and fibre yield. Species choice followed by geology had the largest influence on fibre yield (Figure 1), while aspect and hill slope position played a significant but lesser role (Figure 2). These data, while valuable for forestry demonstrate a need and opportunity to improved wood quality model development.

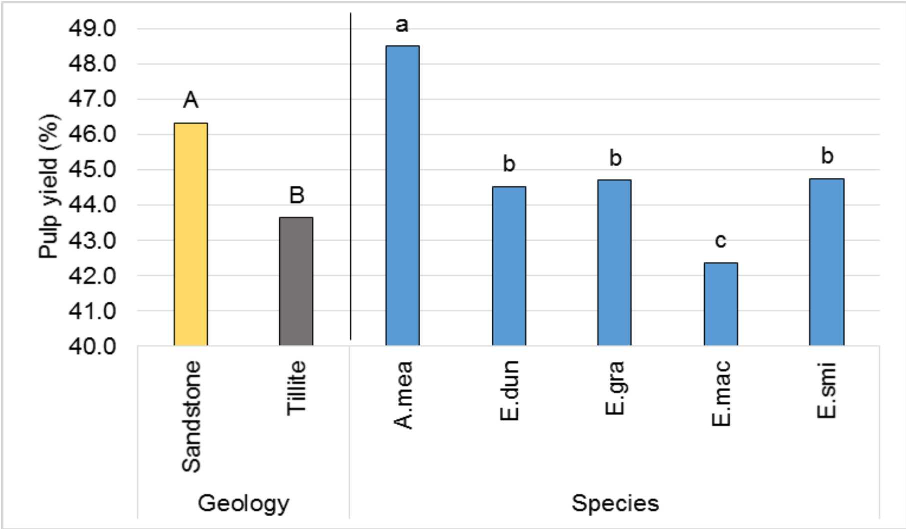

Figure 1: Pulp Yield percentage compared for two contrasting geologies and five genotypes. Different letters denote significant differences for geology (A, B) and genotype (a, b, c) at p<0.05.

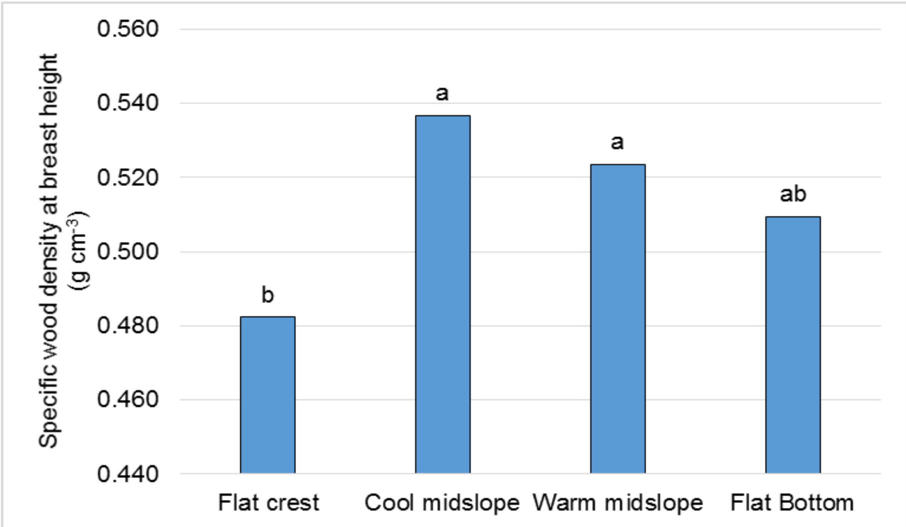

Figure 2: Wood density at 1.3m above ground level along hill slope positions and aspect. Different a, b, c letters denote significant difference at p<0.05.

Further to this are studies by various companies to utilise existing process-based models to improve growth predictions for new and existing sites, improve site classification maps, and separate and quantify the combined impacts of drought and pest damage to trees. Collaborative model parameterisation and validation efforts have developed parameter sets for the 3PG model for specific genotypes (Dicks, 2001; Dye *et al.*, 2004; Esprey, 2005). Although successful, regular changes in genotypes over the years can reduce the value of such studies. A more recent (closed) study utilised the 3PG model, attempting to explain tree growth declines along the Zululand coastal plain. The model partially explained growth decline attributed to water deficit while the compound impacts of pest and disease exacerbated by drought were not quantifiable as a model input. Use of a modelling approach raised interest in using sub-models to hybridise empirical growth and yield models.

Conclusion

Opportunities that models present for improved wood yield and quality prediction, measurement and quality controls that inform preceding and subsequent steps along the forest supply chain, and risk assessment, *inter alia* Development, adoption and use within in the South African forestry industry is motivated by cost, data availability, technology, skills, intellectual property, collaboration and relevance. To succeed a model has to compete with real-time data collection that is becoming cheaper and simpler with advancing technology and traditional systems.

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MODELLING THE IMPACTS OF WATTLE (*ACACIA MEARNSII*) PLANTATIONS ON ECOSYSTEM SERVICES IN SOUTH AFRICA

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Introduction

Commercial forestry in South Africa is based on plantations of fast growing alien timber species like Pine, Eucalyptus and Acacia (Wattle). Besides the potential problem of species invasion towards sites outside of plantations, these exotic species exert a strong impact on ecosystem services delivery at the local, catchment level and regional scale. Among the best studied areas in South Africa, the case of the two streams catchment area is exceptionally rich in data collected over the last two decades. Data collected include tree growth, stand transpiration, above canopy eddy covariance fluxes, stream flow and soil water profiles. As such the two streams catchment area is an ideal test case for the application of biogeochemical (BGC) vegetation models to complement ongoing soil water atmosphere transport (SWAT) modeling.
Within this research we will assess the possible benefits of detailed process based vegetation modelling using field data from wattle plantations within the two streams catchment area, BioGeoChemical ecosystem modelling to assess best options in terms of timber yield, catchment hydrology and their respective temporal dynamics.

Data and Methods

Modelling
Within this research we used the biogeochemistry Management model (BGC-MAN; Pietsch, 2014), which gives a mechanistic description of the cycling of energy, water, Carbon and Nitrogen within a given ecosystem. Briefly, it calculates photosynthesis, assimilation, allocation, growth and maintenance respiration, canopy light and water interception, canopy and soil water evaporation plant transpiration, soil and leaf water potential, water runoff and outflow, nutrient leaching, nitrogen volatilization, decomposition, mineralization and heterotrophic respiration and nitrogen immobilization. Model parameter values for *Acacia mearnsii* plantations were taken from the literature. Daily weather data for running the model where extrapolated from the nearest Princeton global climate data set using MountainClim 4.3 (Thornton and Running, 1999). Nitrogen fixation rates of *A. mearnsii* were estimated taken from the AgroForestree database 4.0 (Orwa *et al.*, 2009). Nitrogen deposition was taken from Dentener *et al.* (2006).

Field data

Field data from *Acacia mearnsii* plantations within the two streams river catchment area, located around 70 km north east of Pietermaritzburg, KwaZulu Natal, South Africa, and were used to calibrate the BGC-MAN model. Soil properties for the catchment area were extracted from the Harmonised World Soil database (*HWSD*; *FAO*/IIASA/ISRIC/ISS-CAS/JRC (2012). Site history and data for comparison of model predictions with field observations were taken from Everson *et al.* (2014).

Simulation Procedure

We first performed a spin up simulation assuming natural grass and shrublands until soil carbon content (i.e. the last among the Carbon pools to reach steady state) did not change by more than 0.5 g m^{-2} between successive simulation periods of 40 years. After the spinup to steady state we simulated *Acacia mearnsii* plantations with 10-yr. rotation length. In 2004 we performed clear cutting for the riparian zone (~7.5ha) and in 2006 a complete clear cut for the rest of the catchment area (~65ha). Successive planting was performed only for the non-riparian zone of the catchment

Results & Discussion

Modelled biomass development of A. mearnsii stands match the data measured on the ground. Comparison of measured and modelled LAI exhibited no bias in model predictions. Given the confidence on model performance on tree growth, we next looked at water consumption by the specific wattle plantation. Trees within the riparian zone exhibited a significantly higher stand level transpiration rate as the trees of the non-riparian zone, where ground water access was absent during the growing season. The 2004 clearing of the riparian zone led a reduction in total water consumption at the watershed level. During the period of clear cutting and replanting of the non-riparian zone in 2006, modelled water outflow increased significantly, but levelled out gradually to pre-clear-cut values within the next five years after establishment of the new plantation.

Our results demonstrate the potential of detailed process-based vegetation models to assess the hydrological impacts of tree plantations at the plot and watershed levels. In combination with detailed SWAT models the use of models like BGC-MAN may help to predict the consequences of a certain vegetation and management type on watershed hydrology and resulting stream flow. Future work will integrate the simulation of additional vegetation types (thickets, grasslands, agricultural land) and related management strategies to assess the impact on watershed hydrology. A comprehensive model testing and validation will further allow to assess scenarios of best practices in spatial arrangement of land use in order to optimize productivity, reduce water consumption and avoid land degradation.

Acknowledgements

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MODELLING TREE-LEVEL MORTALITY OF NOTHOGAFUS FORESTS IN SOUTHERN-CHILE: A MIXED-EFFECTS LEVEL APPROACH

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Introduction

Tree-level mortality is a key ecological process of forest ecosystems dynamics. Trees die as a combination of several factors, usually classified as density-dependent and density-independent. The main density-dependent factor in forest ecology is competition. Habitats are limited by space and resource availability, and can only support up to a certain number of trees before reaching their carrying capacity (Chao et al. 2009). Once a population exceeds that capacity, trees must struggle against one another to obtain scarce resources. Competition in natural populations can take many forms (Franklin et al. 1987). Furthermore, there are stochastic factors (i.e., disturbances such fire, diseases) that are always affecting to forests on space and time. As pointed out by Dennis et al (1985): life is stochastic! Overall, mortality is a key ecological process shaping forest dynamics.

Understanding and predicting tree mortality is critical in both applied and basic ecology (Franklin et al. 1987). Tree mortality is a dynamic phenomenon, only possible to observe by remeasuring trees on time. In order to model mortality we have to analyze time series data collected in permanent sample plots (PSP). Although having access to public and/or freely data on PSP are common in developed countries, they are rare in developing countries. Furthermore, when natural forests are the focus of research, mortality is especially complex because of the many interactions occurring. Not only is modelling tree-level mortality generally a hard task, but it is particularly so when only scarce data are available for modelling efforts. We aim at developing a tree-level mortality model for the main *Nothofagus* species in mixed-species stands of south-central Chile. In order to do so, we focus on (a) identifying the main drivers of tree-level mortality, (b) fitting generalized linear models in a mixed-effects framework to account for the hierarchical structure of the data, and (c) analyzing the biological behavior of the proposed model. We report here our preliminary results.

Materials and methods

A set of 50 permanent sample plots established in secondary forests of *Nothofagus*-dominated stands in south-central Chile (37º 30’ -- 41º 30’ S) were used as data for the present study (Figure 1). Temporal tree-level measurements are used for computing stand-level variables per plot, as well as, several other types of variable were derived. The variables aiming at representing tree size, competition, vigor, density, productivity and climate drivers affecting tree-level mortality.

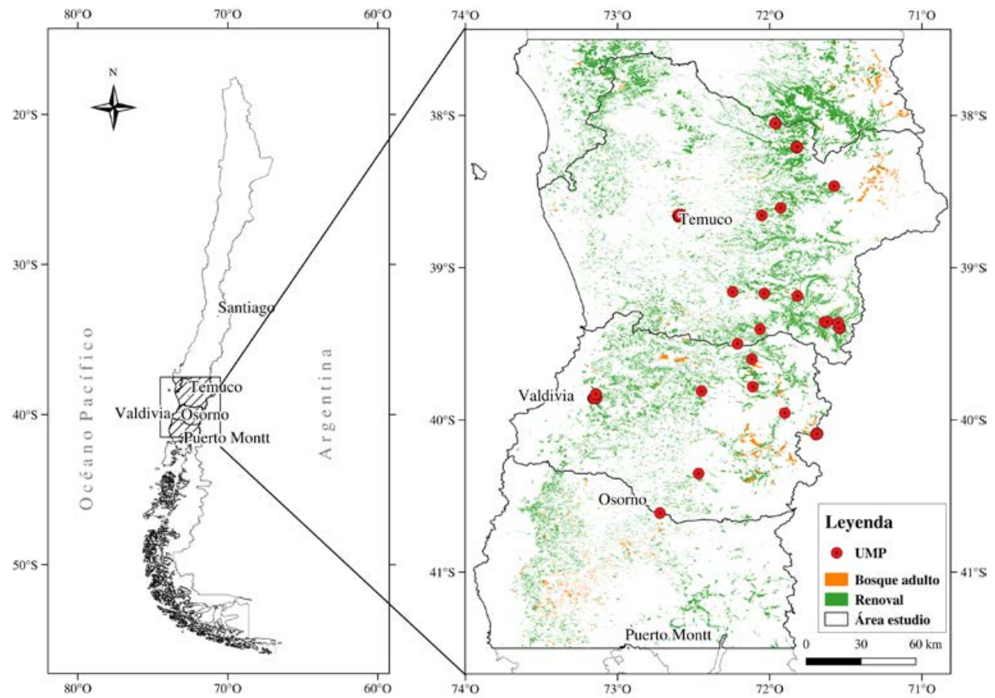

Figure 1: Map of study site locations in south-central Chile.

We assess different mathematical formulations for a base-logistic regression model to predict the dichotomous variable tree-dies/tree-survive in a period length. Based on statistical inferences and prediction capabilities, we proposed a tree-level mortality model, which is assessed for understanding the biological implications of the drivers on tree mortality.

Results

We proposed to use the percentile of the variable basal area in larger trees (BAL) as a proxy for representing competition instead of simply using BAL. The diameter growth rate is a good predictor of mortality, as well as, diameter itself (as a proxy for tree size). The mixed-effects model framework offer us a suitable approach for hypothesis testing of predictors that are not at the tree-level (e.g., site productivity) but are share for trees within a sample plot. Tree species differences are being currently studied, and the behavior analysis of the proposed model had shown a biologically-consistent behavior.

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BRINGING FOREST SIMULATIONS TO LIFE: USING A MANAGEMENT DRIVEN SIMULATOR TO IMPROVE FOREST MANAGEMENT IN PORTUGAL

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Introduction

The supply of forest products and services depends on forest area, forest productivity and on a set of management choices. Bringing growth models that predict forest dynamics under different scenarios of management, policies or climate into stakeholders' lives has become a necessity more than a challenge. StandsSIM.md, a management driven forest simulator (Barreiro *et al.*, 2016), was used in a practical exercise aiming to assess the impact of different management scenarios on wood supply and forest profitability of eucalypt plantations. A small parish in the centre of Portugal struck by a large wildfire in 2017 was selected as the study area. The objective was to show local forest owners that by improving management their eucalypt plantations could become more productive, economically viable and eventually more fire-resilient.

Materials and methods

Over the past decades Alvares parish suffered significant depopulation and land abandonment. During the past 40 years an intense fire incidence was also observed. Before 2017´s fire, which burned around 54% of the area, around 90% of the parish was forested predominantly with eucalypt (52%). Land use and forest tree cover in the study area were obtained from cartography (COS2015). Stakeholders were deeply engaged in the characterization of forest owners/forest management and current forest areas assigned to each forest management approach (FMA). Five types of owners, characterized by different FMAs were defined:

i) Professional industrial owners characterized by intensive sustainable management carry out proper site establishment, use genetically improved material, fertilize, and perform intensive fuel and pest control operations (20% of total area);

ii) Active private owners try to mimic the management practiced by the industrial, managing slightly less intensively than industrial owners, only using genetically improved material in about 80% of the area (10% of total area);

iii) Semi-active private owners focus on site establishment operations, have no access to genetically improved material, perform less to no fertilizations and or fuel control operations (10%);

iv) Close-to-absent private owners simply focus on final harvest (usually anticipated) and benefit from eucalypt re-sprouting ability for site establishment (45%);

v) Absent private owners do not explore their unmanaged shrubby-forests (15%).

The current forest areas by owner type, with different levels of management intensity, correspond to the business-as-usual (BAU) scenario. Forest area must be reduced (create a fuel break network) and management improved in order to obtain a more resilient and productive forest. Thus, three additional scenarios were considered. These scenarios reflect a reduction in forest area combined with increasing levels of management intensification (S0, S1, S2) achieved at the expense of shifts in the areas assigned to some private non-industrial forest owner types (***Table 1)***.

Table 1: Management scenarios considered for the Alvares parish.

Forest owner type	**Level of management intensity**	**BAU (area %)**	**S0 (area %)**	**S1 (area %)**	**S2 (area %)**
Professional	++	20	20	20	20
Active	+	10	10	10	20
Semi-active	+-	10	25	40	35
Close-to-absent	-	45	30	15	10
Absent	--	15	15	15	15
		100	84	84	84

Estimates of eucalypt standing volume overbark (V) and of net present value (NPV) were obtained for the parish running StandsSIM.md simulator under the four scenarios for a period of 36 years. An interest rate of 4% was considered.

Results

The estimates of standing volume overbark at the time of harvest (around age 12) and net present value per hectare were summed for the 36-years' period (**Table 2**). Standing volume overbark increases from the BAU towards the S2 scenario reflecting the impact of increasing the areas of eucalypt plantations more intensively managed.

Table 2: Overall estimates of standing volume overbark and net present value for each scenario.

BAU		S0		S1		S2	
V (m^3 ha^{-1})	NPV (€ ha^{-1} yr^{-1})	V (m^3 ha^{-1})	NPV (€ ha^{-1} yr^{-1})	V (m^3 ha^{-1})	NPV (€ ha^{-1} yr^{-1})	V (m^3 ha^{-1})	NPV (€ ha^{-1} yr^{-1})
274	42.4	301	48.3	311	48.1	315	48.2

Conclusions

Preliminary results indicate that despite reducing eucalypt forest area for creating the fuel break network in the parish it is possible to increase productivity. Results will soon be presented to stakeholders for discussion. Adjustments might be required, and new simulation runs might be needed. Making forest models available for users is essential not only to assist management, but also for research. StandsSIM.md simulator is freely available for download in the FCTools website http://www.isa.ulisboa.pt/cef/forchange/fctools/en/SimflorPlatform) and includes a handbook with hands-on exercises.

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MAPPING RISK AT DIFFERENT SPATIAL AND TEMPORAL SCALES FOR SHORT- AND LONG-TERM RISK EVALUATION: THE CASE OF THE EUCALYPT GALL WASP LEPTOCYBE INVASA

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Introduction

Crop damage, tree mortality and yield loss due to pest outbreaks are serious risks to supply from industrial wood plantations in South Africa. Global trade has increased the pace of new forest pest and pathogen arrivals in southern Africa and global climate change has increased uncertainty around pest impacts for the sector. Spatially explicit ecological niche models with scenario capability can assist in evaluating the risk of pests and pathogens in support of both short-term decision making and long term strategic planning.

This study focuses on the development of modelling techniques to evaluate the ecological niche distribution of the Eucalypt gall wasp *Leptocybe invasa*in the plantation forestry areas of South Africa and predict the risk of outbreaks at different spatial and temporal scales.

Materials and methods

Model building was performed using the package Dismo (Hijmans *et al.,* 2016) in the R statistical software (R development Core Team, 2008). Two ecological modelling techniques were tested (Bioclim and Maxent), both requiring presence data only. For long term risk evaluation, current, intermediate and future climate data were obtained from the Worldclim website (Fick *et al.,* 2017, Hijmans *et al.,* 2005). From these datasets, 19 bioclimatic variables were developed (Hijmans *et al.,* 2016) and used as environmental parameters to define the ecological niche of *L. invasa*under current and future climate change scenarios. A novel approach is being tested to evaluate the actual risk of outbreaks based on current weather using coastal Zululand as pilot area. Monthly grids of rainfall, minimum temperature, maximum temperature, solar radiation and relative humidity were developed for the years 2015, 2016 and 2017 by interpolating data from 20 weather stations located near plantation forests using the package Meteoland (de Caceres *et al.,* 2018) in the R environment (R development Core Team 2008). These datasets are currently being used as environmental parameters to define the climatic niche of *L. invasa* at monthly intervals and identify seasonal and annual changes in risk of outbreaks.

Results

<u>Long term current, intermediate and future climate</u>

Maxent outperformed Bioclim in predicting the risk of *L. invasa* over the forestry landscape, achieving an accuracy of84%. Bioclim's performance was slightly inferior and predicted the likelihood of occurrence of *L. invasa* with an accuracy of 79%. The model highlighted that *L. invasa*'s outbreaks are strongly temperature driven, with warmer climates being more favourable.

Based on available climate change predictions, optimal conditions are likely to expand within the forestry landscape in response to predicted higher temperatures (Figure 1).

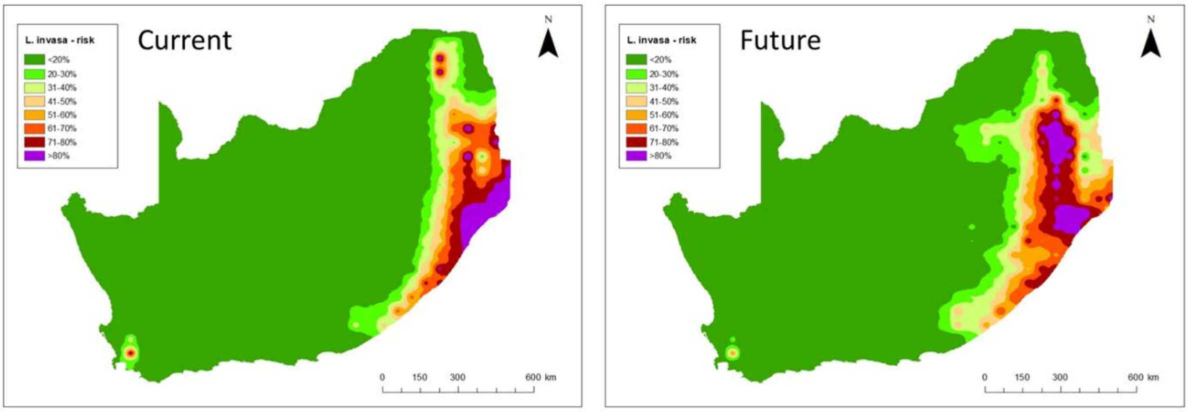

Figure 1: Current (2000-2010) and future (2080-2100) risk of Leptocybe invasa outbreaks in South Africa based on suitable climatic niche distribution.

Coastal Zululand, time series risk: 2017

This work is in progress. Preliminary results show that the modelling approach tested in this study can determine the optimal climatic niche of *L. invasa* based on spatially interpolated point weather data. Yearly and monthly evaluation of suitable climatic niche in the Zululand coastal area achieved an accuracy between 81 and 92%. Monthly changes in niche distribution for the year 2017 are shown in Figure 2. The analyses for year 2015 and 2016 is currently in progress.

Conclusions

Spatially explicit niche models with scenario capability enable us to predict pest and disease outbreaks and to identify hot spots at different spatial and temporal scales. This study attempts to apply novel spatial interpolation and modelling techniques to assess changes in the distribution of the climatic niche of the Eucalypt gall wasp *L. invasa* over the landscape under current and future climate. The model is also used to develop time series at monthly intervals for short term evaluation of risk and potential outbreaks. The ability to develop simple modelling techniques to evaluate biotic risk and predict outbreaks in quasi-real time based on observed weather (as opposed to long term climate averages) opens opportunities for targeted and proactive intervention to minimise the impact of pests and pathogens on growth and productivity of plantation forests.

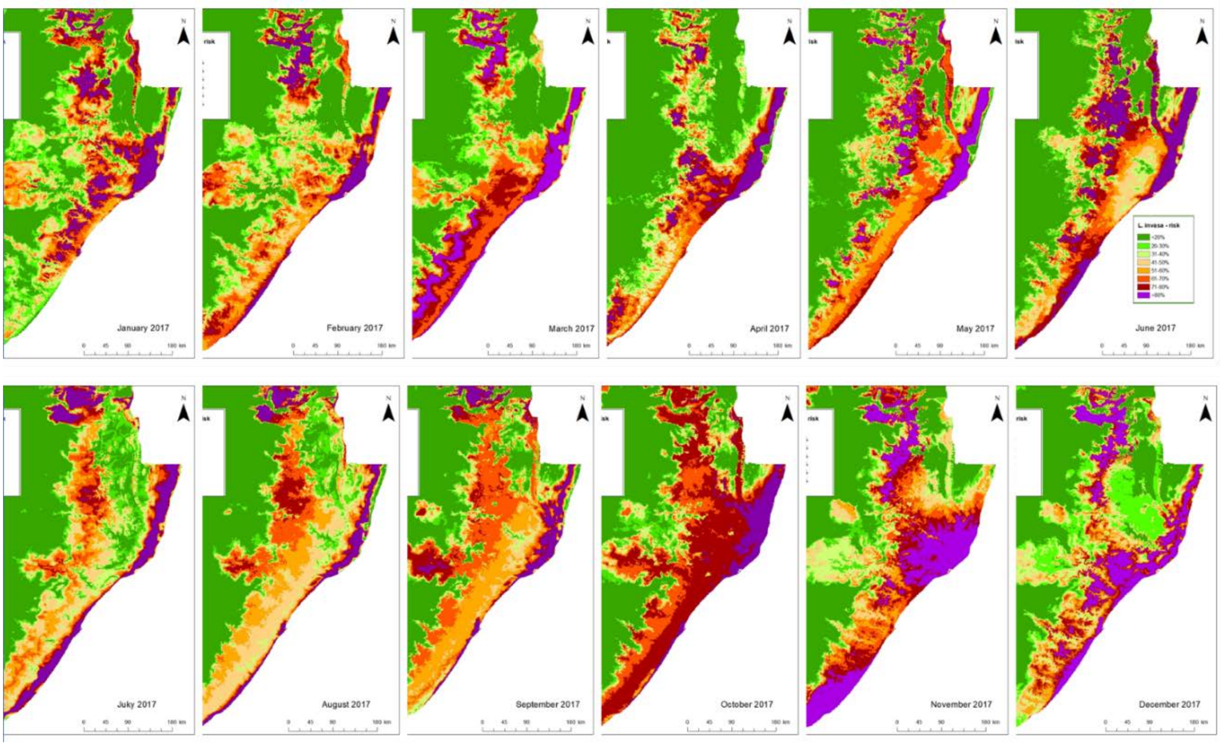

Figure 2: Monthly changes in Leptocybe invasa suitable climatic niche distribution along the Zululand coastal area of South Africa for the year 2017.

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FORECASTING WITH EMPIRICAL STAND-LEVEL GROWTH AND YIELD MODELS AND DROUGHT MODIFIERS FOR SHORT ROTATION EUCALYPTUS PULPWOOD IN MONDI, SOUTH AFRICA

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Introduction

Mondi South Africa is a pulp and paper producer. It grows most of its gum pulpwood timber requirements. The plantations are distributed over three main physiographic areas, namely sub-tropical coastal Zululand, the warm temperate KwaZulu-Natal midlands and the cold-temperate south-eastern part of Mpumalanga. The diverse climatic conditions require species suitable to each climatic region. The plantations are planted, of single species, even-aged and unthinned with a rotation age of about ten years.

To forecast growth and yield, empirical stand-level growth and yield models are used. The major challenges affecting accuracy of growth and yield prediction are droughts and the associated impact of pests and diseases. To estimate yield modifiers, an empirical method using a stratified sample of repeat inventories is used.

The modelling results are illustrated with an example for the *Eucalyptus grandis x Eucalyptus urophylla* hybrid (*Egxu*). The drought experienced in 2014 to 2015 is illustrated for coastal Zululand with its associated drought modifiers.

Materials and methods

Mondi adopted a stand-level modelling approach, summarized herein. The Hossfeld function (Palahi*et al.*, 2004) was selected to model dominant height, the Clutter-Jones (Clutter & Jones, 1980) function to model tree survival and the stand-level basal area function (Pienaar & Harrison, 1989) to model basal area. A simple linear model was used to estimate mean height from dominant height (Kassier, 1993). Multiple linear regression models were used to model standard deviation of diameter at breast height (dbh) (Kassier, 1993) and minimum dbh (Kassier, 1993). The average height by dbh function (Pienaar & Rheney, 1993) was used to model the development of average height by dbh over time as a function of mean dbh and mean height. The segmented polynomial volume and taper function (Max & Burkhart, 1976) was used to model stem profiles and estimate tree volumes (Reed & Green, 1984).

Data for the development of stand-level models for dominant height, basal area, trees per hectare, standard deviation of dbh and minimum dbh are collected from re-measurements of permanent sample plots and long-term spacing trials to ensure sensitivity to site quality and stand density. Data for the stand structure model components for standard deviation of dbh, minimum dbh, mean height and average height by diameter are supplemented from management inventories. Data for the development of volume and taper functions are collected from destructive sampling over the dbh and height range for each species.

Forecasting for a stand is done by calibrating models with an inventory or with site index-based defaults. When an inventory is available, the Nepal-Summers stand table projection method (Nepal

& Summers 1992; Corral-Rivas *et al.* 2009) is used to project and maintain the shape of the diameter distribution. Ratio methods (Observed/Predicted) are used to calibrate and govern the behaviour of minimum dbh and mean height. When no inventory is available, a calibration point is created at site index reference age, given default values for site index, survival and a predicted value for basal area. In this case the dbh distribution is reconstructed using the Weibull method of moments approach (Garcia 1981; Gadow & Bredenkamp 2000).

Yields are modified with empirical modifiers to adjust for drought effects. Stands inventoried in the year before the drought are selected and a repeat inventory is done in the following years. An average volume adjustment factor is calculated by comparing volume of the repeat inventory to volume projected from the first inventory prior to the drought.

Results

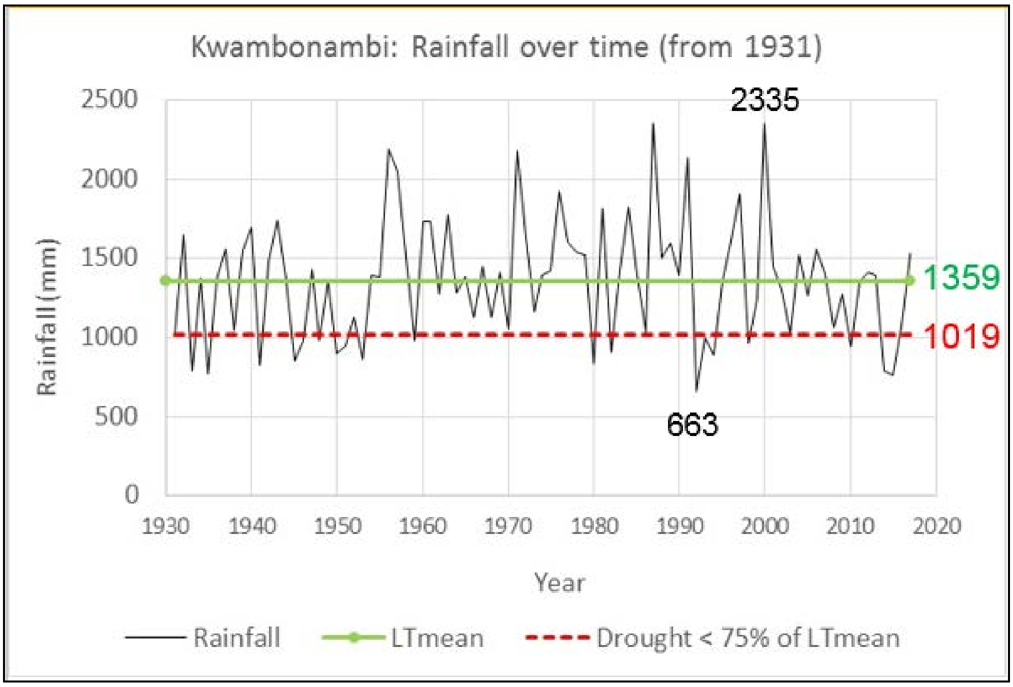
The results for the modelling exercise on *Egxu* (Kotze & Fletcher 2013) are shown in Table 1.

Table 1: Functions to predict stand-level and stand structure attributes.

Attribute	Equation[1]
Dominant height	$HD_2 = AGE_2^2/\left(0.074177 + AGE_2 \cdot \left((AGE_1/HD_1) - 0.023642 \cdot AGE_1 - 0.074177/AGE_1 + 0.023642 \cdot AGE_2\right)\right)$
Mean height	$HM = 1.91604 + 0.89072 \cdot HD - 6.83548 \cdot (Dsdev/Dmean)$
Trees/ha	$TPH_2 = \left(TPH_1^{-0.047704} + 0.020609 \cdot \left((AGE_2/100)^{0.82802} - (AGE_1/100)^{0.82802}\right)\right)^{(1/-0.047704)}$
Basal area/ha	$BA_2 = exp\left(ln(BA_1) - 6.75324 \cdot (1/AGE_2 - 1/AGE_1) + 0.33312 \cdot \left(ln(TPH_2) - ln(TPH_1)\right) + 0.85559 \cdot \left(ln(HD_2) - ln(HD_1)\right) + 0.75451 \cdot \left(ln(TPH_2)/AGE_2 - ln(TPH_1)/AGE_1\right) + 0.072155 \cdot \left(ln(HD_2)/AGE_2 - ln(HD_1)/AGE_1\right)\right)$
StdDev of dbh	$Dsdev = 0.87858 + 0.17123 \cdot AGE + 0.042825 \cdot BA$
Minimum dbh	$Dmin = (0.80906 - 1.97080 \cdot (Dsdev/Dmean) - 0.044623 \cdot (TPH/PSPH) + 0.011475 \cdot AGE) \cdot Dmean$
Average height by dbh-class	$h_i = 1.32618 \cdot HM \cdot \left(1 - 1.16493 \cdot exp(-1.56508 \cdot DBH_i/DBHq)\right)$
Stem profile	$d_{ib} = \sqrt{\left(DBH^2 \cdot (-2.721 \cdot (X-1) + 1.18891 \cdot (X^2-1) - 0.90650 \cdot (0.83117 - X)^2 \cdot I_1 + 95.42845 \cdot (0.059583 - X)^2 \cdot I_2\right)}$ Where: $I_i = 1$ if $X \le \alpha_i$ and $I_i = 0$ if $X > \alpha_i$ $\alpha_1 = 0.83117$; $\alpha_2 = 0.059583$
BA calibration	$BA = exp(-5.31360 + 0.46536 \cdot ln(TPH) + 1.50757 \cdot ln(HD) + 0.65157 \cdot (ln(HD)/AGE) - 0.015644 \cdot SI_{Ref\ age} + 0.0059795 \cdot (TPH/PSPH) \cdot 100)$

[1]*HD_i=dominant height in m at AGE_i; AGE_i=stand age in years where subscript I denotes measurements at Age_1 and Age_2 respectively; HM=mean height; DBHq=quadratic mean dbh; Dmean=arithmetic mean dbh; TPH_i = number of trees/ha at AGE_i; BA_i = basal area/ha at AGE_i; Dsdev = standard deviation of Dmean; Dmin = minimum Dbh; PSPH = Planted stems/ha; h_i = tree height of DBH_i in the stand table; d_{ib} = diameter inside bark at height htag; X= htag/HT; htag = height above ground; HT= tree height; StdDev = Standard deviation;$SI_{Ref\ Age}$= Site Index at reference age;*

The 2014 to 2015 drought in coastal Zululand is illustrated in Figure 1 for the Kwambonambi rainfall station. The long-term mean annual precipitation from 1931 is 1359 mm. A drought index is used to indicate a drought year, when rainfall drops below 75% (1019 mm) of the long-term mean. The 2014 to 2015 drought effect had a significant impact on volume growth.



Year From (Vol_1)	Year To (Vol_2)	Vol Adj Factor	# Repeat Inventories
2014	2015	0.87	168
	2016	0.79	75
	2017	0.72	13

Where:

$$\text{Vol Adj Factor} = \frac{\sum_{i=1}^{n}(\text{Act Vol}_2)_i}{\sum_{i=1}^{n}(Pred\ Vol_2)_i}$$

Vol_2 = Volume at 'Year To'.

Figure 1: Rainfall over time at Mondi Kwambonambi rainfall station with tabular summary of drought effect as expressed by a volume adjustment factor for eucalypts.

Conclusions

Mondi uses a stand-level growth and yield modelling approach. Accuracy of projection from an inventory is improved by calibration of stand-level model components and use of stand table projection methods. Drought effects are estimated with volume adjustment factors. The frequency of drought occurrence is a stark reminder to review the methods for studying and estimating drought effects on growth.

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MODELLING SOIL NITROGEN AND WATER AVAILABILITY TO GAUGE THE RESPONSIVENESS OF SEMI-MATURE PINE TO FERTILISATION IN THE CAPE FOREST REGION, SOUTH AFRICA

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Introduction

Physiological models in forestry usually mimic the interplay of intercepted radiation, water availability, nutrient supply and silvicultural inputs on light interception, light use efficiency and carbohydrate allocation patterns in forests, resulting in a given stand growth rate. However, several models deal only superficially with the complex issue of "soil fertility", often by means of a naïve fertility rating. The cycling of nitrogen (N) in forest systems is significantly affected by climate, terrain conditions (Smethurst *et al.*, 2015), management practices, tree species, soil water contents and other basic soil properties such as texture, organic matter content, pH and the C:N ratio (Arslan *et al.,* 2010; Pulito *et al.,* 2015). Forest management practices, such as cultivation, slash management and thinning significantly affect the nitrogen mineralisation rates of a soil and subsequent N uptake by trees (du Toit and Dovey, 2005; Smethurst *et al.,* 2015). We investigated the combined effect of edaphic, climatic and site management effects on N mineralisation rates in the Cape forest region.

Materials and methods

Eight field trials (labelled A - H) were established in the Cape forest region to test the effects of six N and P fertiliser combinations on the growth response of pines. The treatments (all in kg ha^{-1}) were: 0 N + 0 P (T0), 0 N + 50 P (T1), 0 N + 100 P (T2), 100 N + 50 P (T3), 100 N + 100 P (T4) and 200 N + 100 P (T5). In addition, the soil N-mineralisation rate of each field trial was calculated using the multi-factor Soil Nitrogen Availability Predictor (SNAP) model (Paul et al, 2002). The SNAP model uses estimates of soil water and soil temperature under forest canopies to modify a basal N mineralisation rate (as determined in laboratory incubation studies). Growth responses two years after treatment were correlated to the predicted N-mineralisation rates to determine whether the growth response from fertilisation is significantly affected by the natural N cycling ability of each soil.

Results

The interaction of trial site and fertiliser treatment was significant (p<0.001). The largest responses were observed in field trial D, for treatment T5 (high levels of N in the presence of P), with an increment of 64±3 m^3 ha^{-1} (Figure 1a). On the other extreme, trial site A had the smallest response to treatment T2 (phosphorus only), with a mean increment of 24±1 m^3 ha^{-1}. The annual soil N mineralisation rate predicted by the SNAP model was highest for site A and lowest for site H, with respective values of 238 and 57 kg N ha^{-1} yr^{-1}. The model predicted a mineralisation rate of 92 kg N ha^{-1} yr^{-1} for site D, the most responsive site. It follows that the natural ability of a soil to mineralise N can significantly affect the growth response of semi-mature slash pine to additional N fertilisation. A novel finding for this region was the significant relationship observed between the predicted annual N mineralisation rates and the topsoil pH of each field trial site (Figure 1b). Site A, the least responsive to fertilisation, had the highest soil pH of 4.0. This was the first direct evidence from a comprehensive trial series in the region showing that soil pH might be a growth limiting factor in this region and that it might indirectly affect the optimum (and site-specific) fertilisation rates.

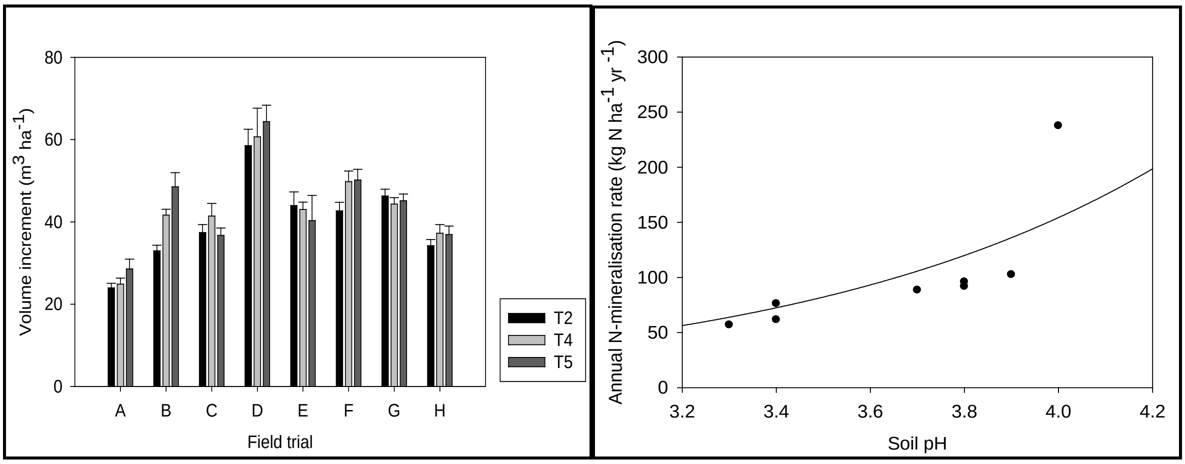

Figure 1a (left): Fertilizer response across trials sites A-H, and 1b (right) relationship between soil pH and predicted annual N mineralisation rate.

Conclusions

The SNAP model identified site A as potentially less responsive to N-fertilisation and the findings of this study confirmed it, however no significant correlation was observed between the volume response to N fertiliser (T4 and T5) and the predicted annual N mineralisation rates. Nonetheless, it has the potential to identify sites that are likely to respond to fertilisation and leaves the possibility for further investigation. Topsoil pH seemed to be one of the main mechanisms behind the observed responses. The effect of soil acidity on the annual N mineralisation rate of a soil leads us one step closer to the formulation of site-specific fertilisation rates in Cape pine plantations.

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SITE FORM AS AN INDICATOR OF SITE PRODUCTIVITY FOR EVEN-AGED STANDS: A CASE STUDY INPINUS RADIATA D. DON STANDS IN NORTH-WESTERN SPAIN

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Introduction

Reliable estimates of site productivity are used as the basis of many ecological and forest management studies. Due to the difficulty in obtaining direct estimates of site productivity, correlated indicators are used in practical applications. The most commonly used indicators are those derived from estimates of stand height at a given age (Skovsgaard and Vanclay, 2008). Site index (SI) is considered one of the most suitable indicators of site productivity for the management of even-aged stands (Rayner and Turner, 1987; Rayner, 1992).Nevertheless, the use of SIis confined to even-aged stands of known age, a variable that is expensive to measure in large-scale forest assessments and is not usually included in most National Forest Inventories (Moreno-Fernández *et al.*, 2018). The site form (SF) is an alternative index to SI derived from estimates of stand height at a given stand diameter (Vanclay and Herny, 1988, Vanclay, 1992, 1994) and has the advantage of being age independent. Although SF can potentially be used for even-aged stands, the practical application of SF is mainly restricted to uneven-aged stands.

In this study, we developed SI and SF models and compared the performance of SF for characterizing the site productivity for even-aged monocultures of radiata pine (*Pinus radiata* D. Don) in north-western Spain.

Materials and methods

The data used in the study correspond to a set of 158 permanent plots established between 1995 and 2003 and subsequently re-measured 2 - 5 times. All plots were located in sites where no thinning treatments had been applied during the period considered. Further details about the plots and sites are reported elsewhere (Castedo-Dorado *et al.*, 2007). The models shown in Table 1 were fitted to dominant height (*H*)-age (*t*) data [1] and to *H*-dominant diameter (*D*) data [2], by using the nested iterative procedure described by Cieszewski and Bailey (2000), to obtain both the global and site-specific parameters. The reference age (t_0) was established as 30 years and reference dominant diameter (D_0) as 30 cm.

Table1: Models fitted to the data. SI: Hossfeld IV GADA [1]; SF: Hossfeld IV ADA [2]

Model		Site-spec. pars.	Dynamic equation
$H = \frac{a_1}{1 + a_2 t^{-a_3}}$	[1]	$a_1 = b_1 + X$ $a_2 = b_2/X$	$X_0 = \frac{1}{2}\left[H_0 - b_1 + \sqrt{(b_1 - H_0)^2 + 4b_2 H_0 t_0^{-b_3}}\right]$ $H = \frac{b_1 + X_0}{1 + \frac{b_2}{X_0} t_0^{-b_3}}$
	[2]	a_1	$H = 1.3 + \frac{Y_0\left(1 + a_2 D_0^{-a_3}\right)}{1 + a_2 D^{-a_3}}$

The fitted models were used to estimate the values of SI and SF for each plot and inventory, as well as the mean value per plot. The SI and SF values were then standardized by using the maximum value of SI or SF across all plots and the standard deviation of the SI and SF values computed for each plot. Correspondence in the ranked classification of the plots by SI and SF was tested using the Spearman's rank correlation coefficient. Similarities in the uncertainty associated with the determination of SI and SF for each plot were compared by correlating the SI and SF estimates for each plot.

Results

Figs. 1a, 1b illustrate the performance of the models fitted to the data. Both SI and SF models performed well over the observed trajectories. The SF models produced steeper sloping lines for the height-age relationship than produced by the SI models, which can be attributed to the ontogenetic phase of the stands under study.

Figure 1c shows the relationship between the standardized SI and SF predictions for each plot. The Spearman's rank correlation coefficient (0.652, p < 2.2e-16) was greater than that obtained by Fu *et al.,* (2018) for natural uneven-aged forests. The error bars in Figure 1c show the relative standard deviation of the SI and SF predictions among inventories for each plot. The predicted SI and SF values did not vary significantly over several re-measurements of the same plot (ρ=0.672; p<2.2e-16). This shows a similar level of uncertainty in the determination of both SI and SF from a single assessment. Standardized values of SI and SF were significantly linearly related to the basal area increment for each plot (p<0.001), as observed by Vanclay (1988), indicating that both indexes are correlated with site productivity. The correlation between SF and other measures of site productivity has previously been observed in natural stands (Vanclay and Herny, 1988).

Conclusions

Site form and site index models were developed for even-aged monocultures of radiata pine in north-western Spain. Site form provided consistent site productivity estimates for even-aged stands, with identical performance to site index when stand productivity was expressed as the basal area growth. Both techniques showed comparable variability within estimates for different re-measurements of the same plot. This methodology can be used for large-scale monitoring exercises in areas with even-aged stands, when the direct measurement of stand age is either not possible or is impractical.

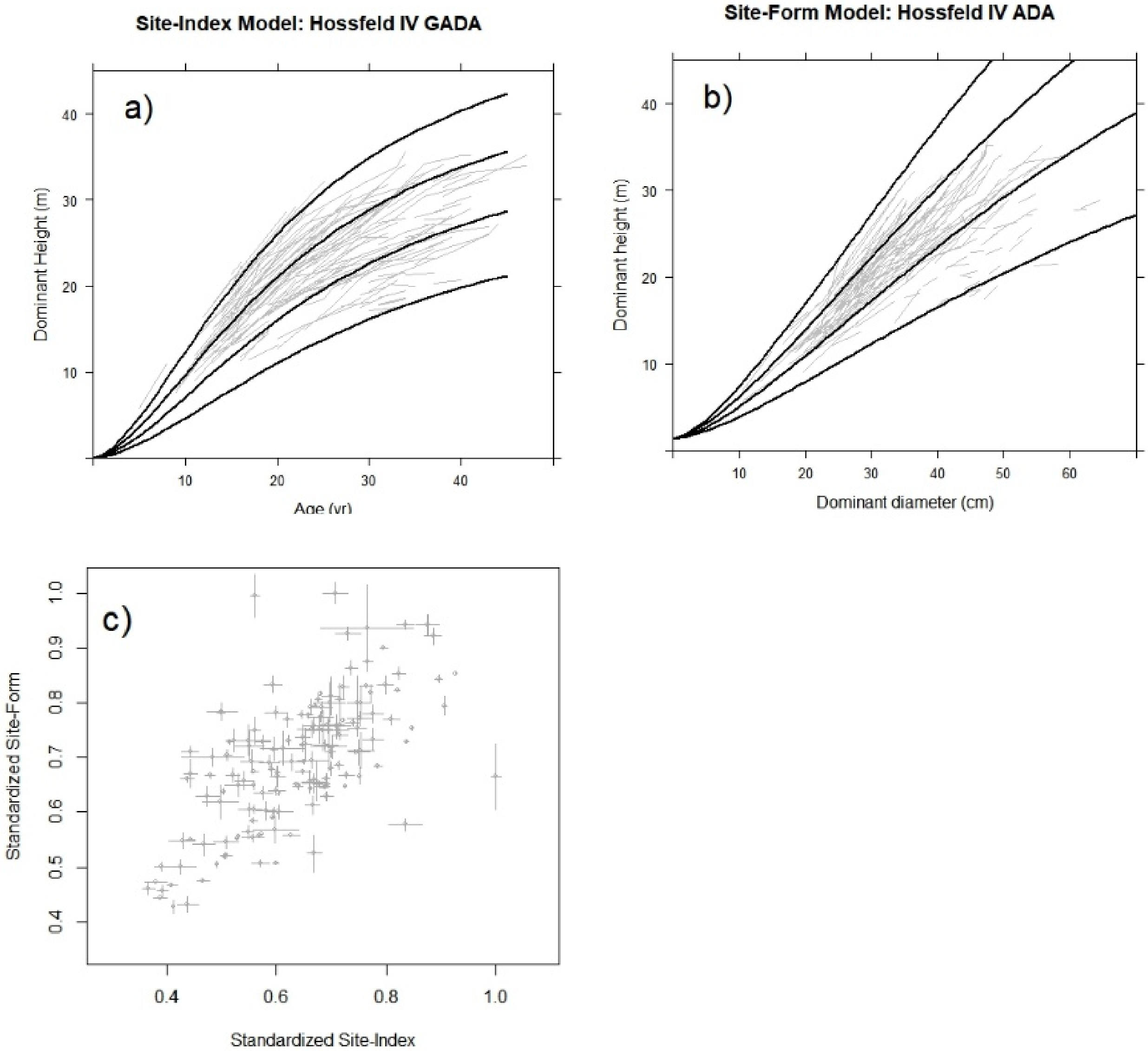

Figure 1: Performance of the a) SI and b) SF models fitted to the data. c) Relationship between the standardized SI and SF predictions.

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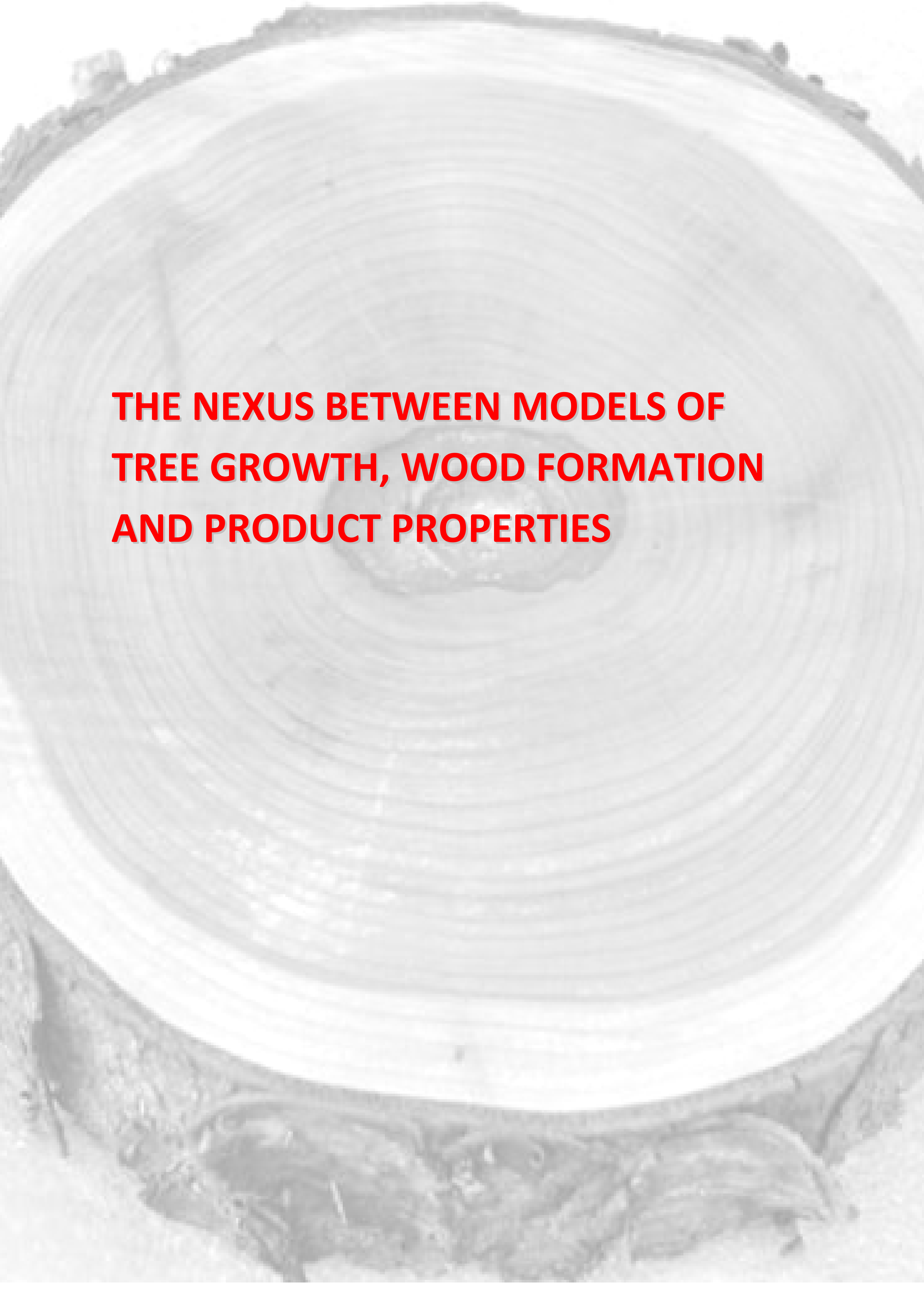

THE NEXUS BETWEEN MODELS OF TREE GROWTH, WOOD FORMATION AND PRODUCT PROPERTIES

KEYNOTE: THE NEXUS BETWEEN MODELS OF TREE GROWTH, WOOD FORMATION AND PRODUCT PROPERTIES

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Statistical, conceptual and inferential models have many applications in forestry, ecology, biology, and related fields. These include understanding physiological processes (e.g. xylogenesis, xylem conductivity), investigating relationships between variables (e.g. tree growth and climatic factors, or drought and xylem cavitation), or for predicting forest growth and yield, intrinsic wood properties and end-use product characteristics. While it is impossible to unify these diverse applications into a single modeling framework, many methodological considerations remain consistent across all of them, and huge advances have been made in recent decades that reflect the exponential increase in computer processing power, and the proliferation of sophisticated learning algorithms.

Rather than give an exhaustive account of different modeling approaches, here I will attempt a walkthrough of some important aspects of wood formation and wood properties modeling, and recent efforts linking them to growth and yield models and product properties. Along the way, I will selectively highlight work by various research groups in these fields, particularly those that have attempted to integrate such models. I will also look at some recent technological innovations for the direct or indirect measurement of wood properties, and how these are furthering our knowledge of wood quality variation, modeling and prediction, particularly in assessing future forest conditions and desired wood properties for some specific end-uses.

DRIVING FACTORS OF WOOD FORMATION IN PINUS RADIATA.

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Introduction

Wood formation and wood properties can be better understood if linked to developmental processes on the level of the entire tree, e.g., carbon allocation, shoot and foliage development, and the corresponding environmental variables that modulate the ongoing growth processes. Those relationships can be captured simultaneously in a "functional-structural tree model" as presented by Fernández *et al.* (2011), or in models like "Cambium" (Drew and Downes, 2015) that simulates xylogenesis, among others. Here, we present the results of the modelling of seasonal xylogenesis dynamics with Generalized Additive Mixed Models and its relationships to environmental variables and crown formation in *Pinus radiata*.

Methods

The development of foliage, main apex and wood of 38 9-year-old *Pinus radiata* in an unmanaged stand for a complete growing season (June of Year 2009 to August of Year 2010). The site has a Mediterranean climate in the central region of Chile (34°40'12.52"S and 71°57'55.04"W) with a 6 months period of drought. Each 15 days at the beginning of the growing season and each 30 days later on, one microcore (2mm diameter x 12 mm length) from each tree was collected using the Trephor tool (Rossi *et al.,* 2006). Thin sections of 20 µm thickness were cut with the microtome, double-stained with safranin and astra blue and mounted on microscope slides using Canada balsam. To distinguish between cells with primary and secondary cell walls, the slides were scanned in both, visible and polarized light with a resolution of 0.49 µm px^{-1}using a colour camera (Nikon DS-Fi2, 5 megapixels and 12-Bit colour depth, Nikon Corporation, Düsseldorf, Germany) mounted on aNikon Eclipse Ni-E transmission light microscope. Following Rathgeber *et al.* (2011) the number of cells in the cambial zone and enlarging cells of the ongoing season were counted. Maturing and already mature cells were counted together, due the impossibility to differentiate between both in the samples. Cell production and development were modelled by Generalized Additive Mixed Models with day of year as fixed effect and individual trees as random effect (Cuny *et al.,* 2013).

Measurements of main apex length and foliage development were done concurrently during each sampling date. At each occasion, three sample trees were felled, their tree architecture described and measured, and discs from each growth unit collected for further wood ring analysis. The foliar biomass was collected and measured. Hourly environmental data were recorded at a nearby weather station, and a climate water balance was calculated.

Results

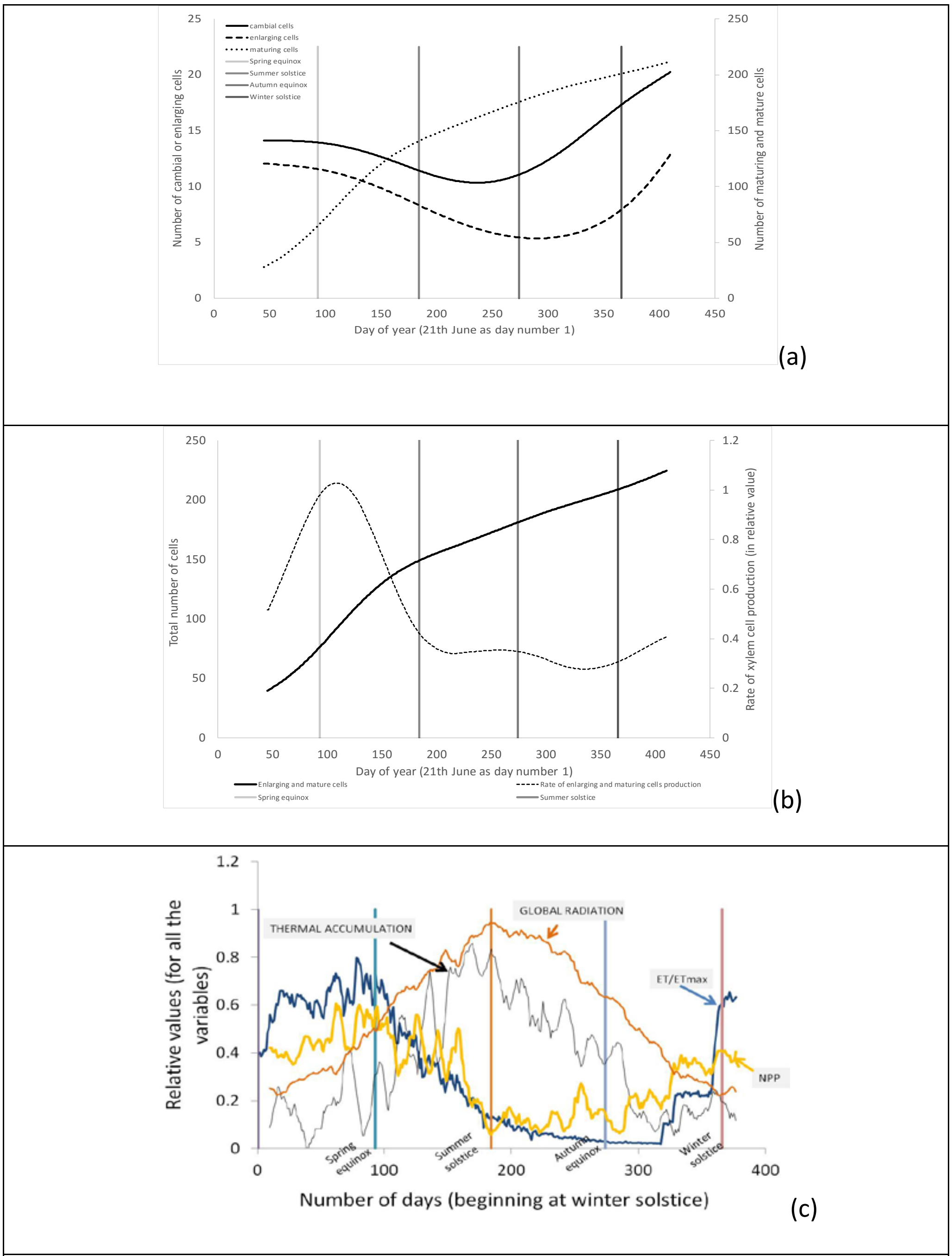

Figure 1: (a) Number of cambial cells, enlarging cells and maturing and mature cells along the year; (b) number of enlarging and maturing and mature cells along the year and rate of cell production; course of thermal accumulation, global radiation, water balance and net primary production; (c) courses of global radiation, water balance (ET / ETmax), NPP (Net Primary Production) and thermal accumulation

Figure 1a shows the number of cambial cells, enlarging cells and maturing and mature cells along the year. Vertical bars correspond to equinoxes and solstices dates (Southern Hemisphere). Figure 1b shows the number of enlarging and maturing and mature cells along the year, and the rate of cell production; as predicted by Generalized Additive Mixed Models. Figure 1c shows the courses of, global radiation, water balance (expressed as the ratio between the evapotranspiration ET and maximum potential evapotranspiration ETmax, NPP (Net Primary Production) and thermal accumulation, using a gamma function (Yan and Hunt 1999) during the sampling year.

Discussion

The Generalized Additive Mixed Models adequately described the cambial activity and particularly the second peak of xylem cell production during autumn. This behavior has been already observed in other Mediterranean species (Camarero *et al.* 2010). In our case, it corresponds to the rise of Net Primary Production (as estimated with the model proposed by Fernández et al, 2011) (NPP in Figure 1c), due to the better growing conditions given in autumn because of early rainfalls and less evapotranspiration. Further data and discussion about the relation between xylogenesis, environmental variables and foliage and stem expansion data (here not shown) will be presented and discussed.

Acknowledgment

Research financed by Chilean Research Grants FONDECYT project number 11085008. M.P. Fernández thanks also for the support of the Project SuFoRun "SuFoRUn: Models and decision SUpport tools for integrated FOrest policy development under global change and associated Risk and Uncertainty", a Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) Call: H2020-MSCA-RISE-2015, in the prosecution of this research.

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THE LINK BETWEEN WOOD PROPERTY VARIATION AND LUMBER STIFFNESS: THE EFFECT OF INITIAL SPACING

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Introduction

One of the most important strategic decisions forest managers make during the plantation establishment phase is the appropriate choice of spacing. The resulting growing space available to trees is one of the major factors limiting the full realization of the genetic potential of a tree. Initial spacing is also the most powerful management tool available to influence the raw material properties of wood and their within-tree variability, which in turn are major determinants of lumber performance. The management of fast growing plantations has generally focused on wood volume production with less concern for the nature and variability of solid wood properties, thereby inadvertently reducing the mechanical properties, particularly the stiffness, of recovered products. Pronounced changes in the stiffness, referred to as the modulus of elasticity (MOE), of juvenile wood, can be largely accounted for by variations in basic wood properties: wood density, microfibril angle (the angle of microfibrils with respect to the vertical axis of the cell, MFA), ring width and knot properties. Therefore, the objective of this study is to examine the effects of changes in growth rate of *Pinus patula*, as mediated through initial spacing, on the within-tree variation of microfibril angle (MFA) and density. We also aimed to evaluate the effect of the resulting variation of density, MFA and knot properties on lumber performance – particularly MOE.

Materials and Methods

The study makes use of data on wood and lumber properties of 45 trees from an 20-year-old *Pinus patula* spacing trial located within the Mpumalanga escarpment (25.7667° S, 31.2392° E), which includes a wide range of tree spacing (1.83 x 1.83 m, 2.35 x 2.35 m, 3.02 x 3.02m and 4.98 x 4.98 m). A 2.4 m saw log was removed above a breast height disc for all trees before being processed into 208 38x114 mm boards using a cant sawing pattern. The pith-to-bark properties of density, MFA and ring width of individual trees and year rings was measured at DBH level by the Silviscan 3 apparatus of CSIRO in Australia. Modified logistic and exponential non-linear mixed effects models, with trees as random effects, were used to evaluate the effect of initial spacing on the within-tree variation (pith value, radial rate of change and an outerwood value) of MFA and wood density as a function of cambial age. Ring width was subsequently also included in the predictions of ring-level properties to validate whether growth rate is sufficient in accounting for differences in tree spacing. Average MFA and density properties were also linked to lumber MOE through the corresponding annual rings present in the board of the same tree from which it was processed. Lumber MOE was then regressed against multiple wood properties, including knot characteristics, using a linear mixed effects model.

Results and Discussion

Preliminary results indicate that MOE improves significantly with reduced spacing. MFA, density and the number of knots per board proved to be the best predictors of lumber MOE (r^2 = 0.73, and 0.82

with random effects) with MFA and density having the highest explanatory power as expected. The only significant difference in the radial variation of both MFA and density between spacing treatments was the radial rate of change. Radial gradients of MFA and density were significantly lower for the 4.9 x 4.9 m treatment. Ring width contributed significantly to the MFA model only; however, there remained significant differences in the rate parameter. These results suggest that growth rate alone may have limited use as proxy for spacing in terms of its effect on MFA and is not a significant causal factor in density variation between spacing treatments. The annual Slenderness of trees were also made available and, in subsequent analysis, will be included in predictions and evaluated as a mechanical casual factor. Given the low stiffness of SA pine lumber associated with reduced harvesting ages and the high variability of basic wood properties in juvenile wood, the results of this study aids in understanding the key drivers of lumber stiffness and how changes in these properties caused by changes in growth, influences end product performance. An accurate model of MOE will enable wood processors to predict mechanical properties of trees from individual sites and plan their production accordingly. It will ultimately assist the sawmill industry to process acceptable structural products from SA pine, specifically *Pinus patula* – a species which dominates the structural lumber market. The final results will be presented after further analysis.

QUANTIFYING THE IMPACTS OF ELEVATED CO_2 AND NITROGEN FERTILIZATION ON XYLEM ANATOMY IN LOBLOLLY PINE

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Introduction

Environmental factors influence the density of tree rings in conifers species (Vaganov *et al.*, 2006). Understanding such effects is necessary to estimate annual biomass increment, and hence forest productivity, but also to determine wood quality. Water transport by the xylem is also affected by environmental conditions, as liquid phase water transport in tree rings is coupled to gas-phase transpirational water loss via the stomatal response at the canopy level. Because atmospheric CO_2 concentrations and nitrogen (N) deposition rates have increased over the last decades and has been shown to affect stomatal functioning, understanding the wood density and hydraulic transport responses of trees can help predict the ecological and industrial implications of such atmospheric changes.

The main goal of this study was to investigate xylem anatomical responses to elevated CO_2 ($^eCO_2$) and N fertilization on loblolly pine (*Pinus taeda L*) using high-resolution tree-ring archives from the Duke FACE (Free-Air CO_2 Enrichment) experiment. We focused primarily on two xylem traits i.e., wood density and xylem specific hydraulic conductivity (ks). Le former is considered a good indicator of wood quality while the latter relates to the hydraulic transport capacity of the xylem. Both parameters can provide information about future physiological response to global changes. As the period covered by the experiment contains at least one reported dry year (McCarthy *et al*., 2007), we expected other climatic variations such as drought occurrence to cause fluctuations in the xylem response to $^eCO_2$ and N.

Materials and methods

Twelve trees were planted in 1986 in the Duke Forest on the North Carolina Piedmont Plateau, USA. Three FACE rings were sampled in both ambient air and CO_2 enriched air conditions (+200 ppm of CO_2 above ambient from 1996 to 2010). Nitrogen deposition was simulated in the form of ammonium nitrate (NH4NO3) fertilization from 2005 (11.2 g m^{-2} yr^{-1}) in one half of every ring. Breast height discs were sampled in 2011 for analyses. Pith-to-bark anatomical analyses were performed on 30 µm thick wood slices.

Wood elative density was estimated using the approach proposed by Vaganov (2006), which consists of estimating the ratio of cell wall area to the total cell area multiplied by the specific gravity of the cell wall (set at 1 kg m^{-3}). Specific conductivity was estimated using Poiseuille's law as proposed by Tyree *et al*. (1991).

Results

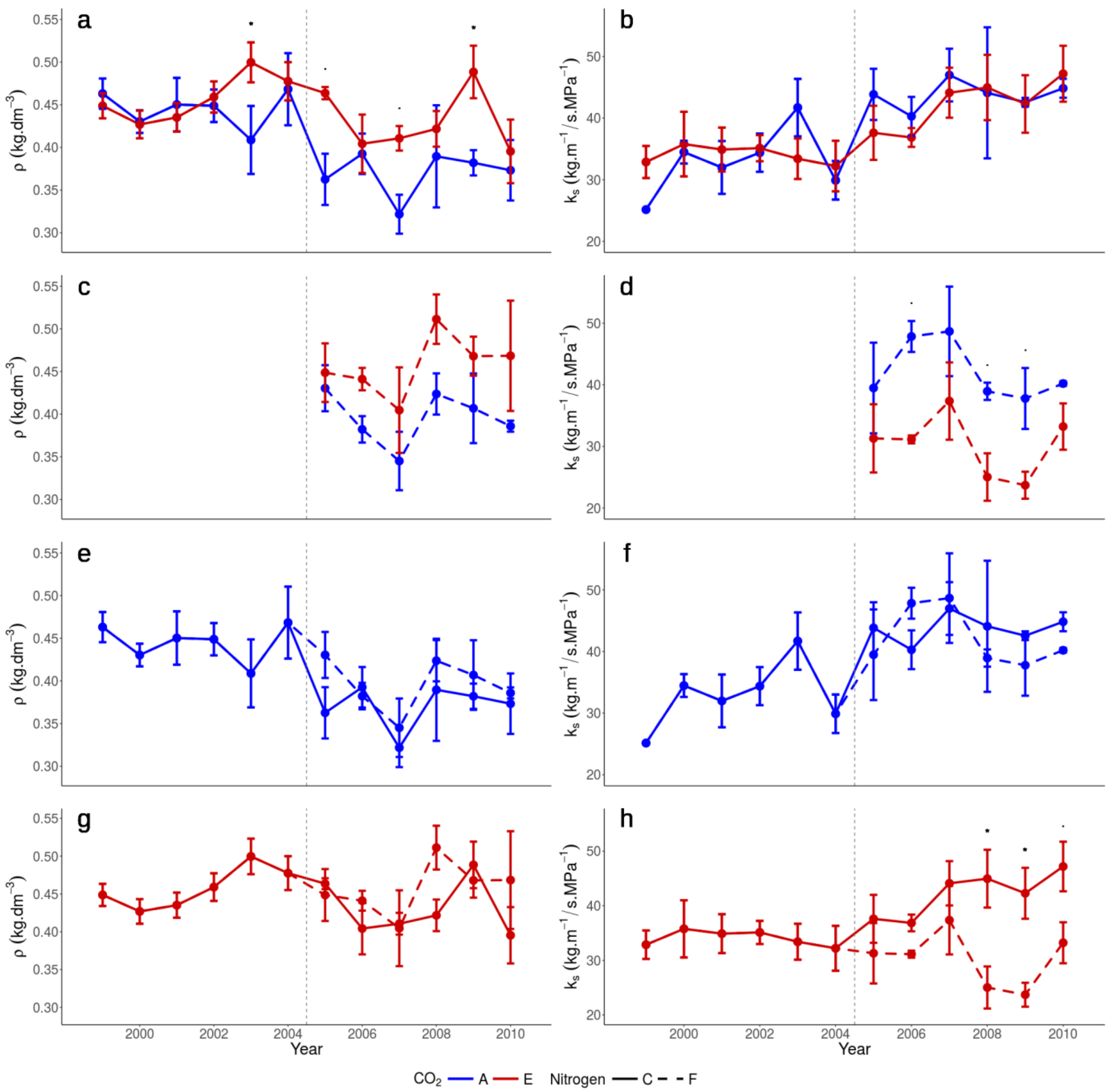

Figure 1: Wood density (left) and specific conductivity (right) during the 12 years of experiment. Pair of treatment combinations display results: ambient (A) or elevated (E) CO_2 with either control (C) or fertilized (F) nitrogen

All trees showed high inter-annual variation of density (from 0.3 to 0.5 kg dm^{-3}). However, no clear trends over the time of the experiment was observed. For the AC treatment (Figure 1a), years 2003, 2005 and 2007 are characterized by a decrease in density compared to their adjacent years. Over the full course of the experiment, $^{e}CO_2$ and N did not impact significantly the density values. However, figure 1a shows that density was higher for the EC treatment EC compared to AC in 2003, 2009 (p<0.05), 2005 and 2007 (p< 0.1). The magnitude of the density gain induced under eCO2 during these four years averaged 0.095 ± 0.041 kg dm^{-3} $^{e}CO_2$ was also associated with a slight increase in wood density when N fertilization was applied (AF vs. EF, Figure 1c), but this observation was not statistically significant. In conditions of either ambient or elevated CO2 (Figures 3e and g, respectively), nitrogen fertilization did not impact density in any of the six years of treatments.

In all treatments, measured k_s also showed a high inter-annual variation, ranging from 2 to 4 kg $m^{-1} s^{-1}$ Mpa^{-1} $^eCO_2$ alone did not induce any significant change in k_s compared to ambient CO_2 concentrations (Figure 1b), and no effect of nitrogen fertilization was found in the case of ambient CO_2 (Figure 1f). In the presence of N fertilization, $^eCO_2$ induced a statistically significant decrease of k_s in 2006, 2008, and 2009 ($p < 0.05$) (Figure 1d). In 2010, k_s in treatment EF was also lower than in treatment EC but only a marginal significance was found ($p < 0.1$).

Conclusions

The absence of a clear response in wood density following both treatments suggests that carbon allocation to the tracheid's cell wall is not systematically affected by $^eCO_2$ and N fertilisation in mature loblolly pine trees. On the other hand, responses to such environmental changes are likely to depend on inter-annual fluctuations of climatic variables. The previously reported drought year of 2002 at the same site (McCarthy *et al.*, 2007) suggests that soil water availability can partly explain the differences in xylem response to $^eCO_2$. However, N availability does not seem to interact with the $^eCO_2$ effect on density during drought years. Hence, cambial activity responses of loblolly pine to global changes must be considered in the context of inter-annual variability of other environmental factors such as precipitation or temperature.

Specific conductivity (k_s), a proxy for hydraulic transport capacity, was negatively affected by the interaction of $^eCO_2$ and N compared to $^eCO_2$ or N alone during the late years of the experiment. This seemed to arise from a long-term response involving the reduction of lumen diameter in such conditions (Domec *et al.*, 2017). This could have implications for the water cycle of the sand and tree growth, as lesser ks is linked to lesser water transport, the latter being a regulating factor of both vertical and radial expansion.

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MODELS OF AGE AND WEATHER EFFECTS ON NUMBERS, WIDTHS AND COARSENESS OF TRACHEIDS AND GROWTH OF YOUNG NORWAY SPRUCE

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Introduction

Annual growth, fibre and wood properties are under strong influences from genetics, age and weather. They change dynamically, particularly at young ages. Most genetic research and tree improvement programs are based on data from this dynamic phase of the life of trees, affected by differences in weather among sites and years. In the presented work, such influences were studied for young Norway spruce trees, and modelled at the detail of annual rings and their compartments earlywood (EW), transitionwood (TW) and latewood (LW), focusing on tracheid numbers, widths and coarseness (biomass/unit length, expressing biomass allocation at cell level), and radial growth.

Materials and methods

Increment cores were sampled at age 21 years from almost 6000 Norway spruce trees of known genetic origin, grown on two sites in southern Sweden (Chen *et al.*, 2014), and analysed with SilviScan. Trees of different longitudinal growth reach breast height at different ages, meaning that rings with same cambial ages are not formed same years, but influenced by different weather conditions. Therefore, the trees were divided into classes on at what age they reached breast height (Lundqvist *et al.* 2018). The mean developments for the traits were calculated for all class and studied versus both cambial age (CA) and total tree age (TA) for comparison, shown in Figure 1 for ring widths, radial tracheid widths and coarseness, for trees reaching breast height at ages 4-8 years, respectively.

General additive mixed models (GAMMs) with an autoregressive element and a hierarchical structure in the random model part were fitted to model the influences of age and local weather. CA and TA were compared as independent variables to model age related influences.

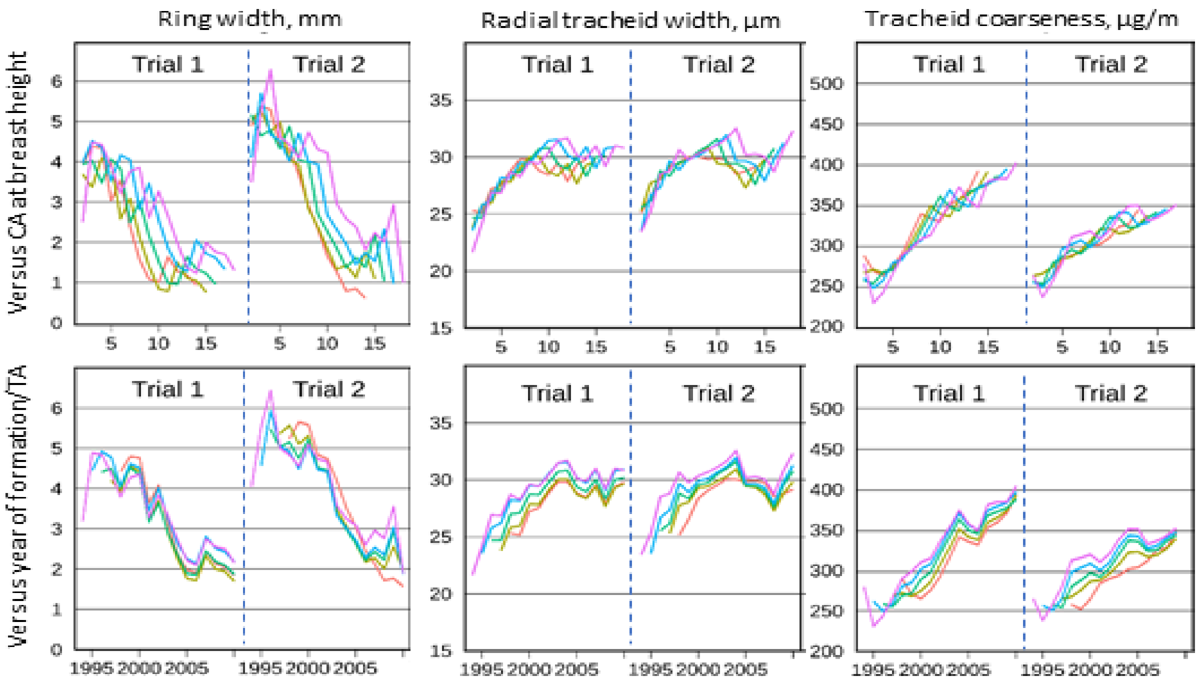

Figure 1: Variations with time of annual means for numbers (left) and widths (mid) of tracheids radially, as well as widths of rings (right), plotted versus cambial age and total tree age, which relates to year of wood formation.

Results

After comparison of different model structures and sets of independent variables, six input variables were used to estimate the trait variations in relation to their averages: Age (TA or CA), temperature sum across the vegetation period (GDD) and precipitation sums for four equal length parts of the period (Psum1-4). Site and family influences are being analysed separately in genetic studies. The highest R^2 values were obtained for number of tracheids formed radially per year (0.53 using TA), radial tracheid width in earlywood (0.44 with CA), ring width (0.43 with TA) and tracheid coarseness (0.42 with CA). The models are illustrated in Figure 2 by influences on numbers of tracheids radially in rings, EW, TW and LW, according to the models. On average 120 tracheids were formed radially per year; At tree age 5 years on average 120 more than that average, in total 245, at age 15 years 40 less tracheids, in total 80, a very large relative variation. Superimposed on this was a positive GDD effect from -15 to +15 tracheids across the span of GDDs, 10% of the extreme events at each end excluded, similar effects of precipitation from mid-June to late July (Psum2), each effect corresponding to ±0.3 to ±0.4 mm in ring width, but smaller precipitation effects during the rest of the year. The adverse was observed for radial tracheid width: Limited relative variation and dynamics closer related to CA were observed, meaning that ring width was largely governed by the number of tracheids formed. The decreasing intensity of tracheid formation was associated with increasing width and coarseness.

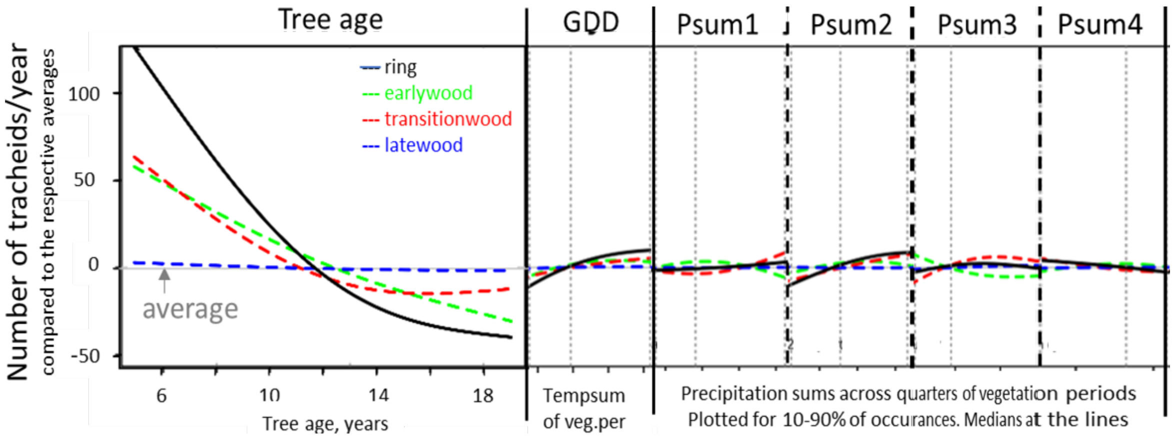

Figure 2: Influences of age, temperature sum across the vegetation period (GDD) and precipitation sums across four equal length periods of the vegetation period (Psum1-4) on number of tracheids formed radially per year and how they distribute as earlywood, transitionwood and latewood.

Conclusions

The study of young Norway spruce trees showed that the number of cross-sectionally formed tracheids at breast height was mostly related to the total age of the tree. Trees that reached breast height late had also the competitive disadvantage of forming thinner rings from the start. The cross-sectional dimensions and biomass allocated were in turn stronger related to cambial age. Weather related influences of temperature and precipitation had a lesser but significant contribution. The results indicate that this type of models can be used to harmonise data from experimental sites with systematic differences in weather and between years, to refine data prior to evaluations to follow, maybe also for estimation of effects on different genotypes from climate change scenarios.

Acknowledgement

The work was performed within the Swedish Strategic Research Program Bio4Energy. Thomas and Stefan Seifert additionally want to express their gratitude to the EU funded RISE project “Care4C”, which provided an excellent platform for scientific discussion.

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TOWARDS MAPPING WOOD PROPERTY VARIATION WITHIN A EUCALYPT PLANTATION TO BETTER MANAGE PULP FIBRE SUPPLY

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Introduction

Several new technologies offer the opportunity to cost effectively map the wood properties in short rotation, intensively managed plantations. One such instrument is a Near Infrared (NIR) spectrophotometer. High dimensional NIR spectral data can detect multi-traits of chemical, physical, mechanical and anatomical properties of wood materials cheaply, rapidly and reliably (Downes *et al.,* 2011; Schwanninger *et al*., 2011). Another instrument, the Resistograph, is of interest as it has provided good density data of standing trees, non-destructively (Gantz, 2002; Eckard, 2007). This instrument was originally designed to measure wood decay through change in resistance. Work done on selected Pine and Eucalypt species showed very good correlations between the actual measured density and the Resistograph measurements. This paper proposes the use of these techniques develop models that would allow the mapping of forest plantations based on selected wood properties.

NIR and Resistograph Model development

Sappi has developed several NIR base models (screened dissolving pulp yield, α-cellulose and total lignin content) using sawdust sampled from either wood disks or from cores in standing trees. The NIR models for pulp yield had a R^2 calibration of 88.28 with calibration error of 0.454 and R^2 validation of 76.9 with validation error of 0.802. Total lignin had an R^2 of 0.88 while the model for α-cellulose showed a R^2 calibration of 76 with calibration error of 1.5 and R^2 validation of 87 with validation error of 1.2. These models provide a quick and inexpensive method of estimating phenotyping wood property traits in the forestry industry, particularly for breeding where large numbers of trees are required to be tested.

A study using 90 trees from a *Eucalyptus dunnii* provenance trial was used to test the Resistograph under local conditions. There was a good correlation between the single point density value (cores and wood disks) and the averaged resistance obtained from the Resistograph. The Resistograph adjusted measurements correlated best with the measured core density (R^2 = 0.80). The preliminary results from this study are presented, and concurred with other studies (Gantz, 2002; Eckard, 2007), that indicate that the Resistograph may be used for determining wood density.

Wood property variation even within varieties planted across sites

Several plantations situated in the sub-tropical coast of Northern KwaZulu Natal are exclusively planted to a small number of productive *E. grandis x E. urophylla* varieties. It would be expected that the wood properties of each individual variety would be highly uniform with any variation within this small geographical area, with any differences due mainly to genetic differences between varieties.

However, in several recent studies, wood density and pulp yields differed substantially between sites situated only a few kilometres apart. Varieties planted on better sites were characterised by having lower densities and higher pulp yields (Figure 1).

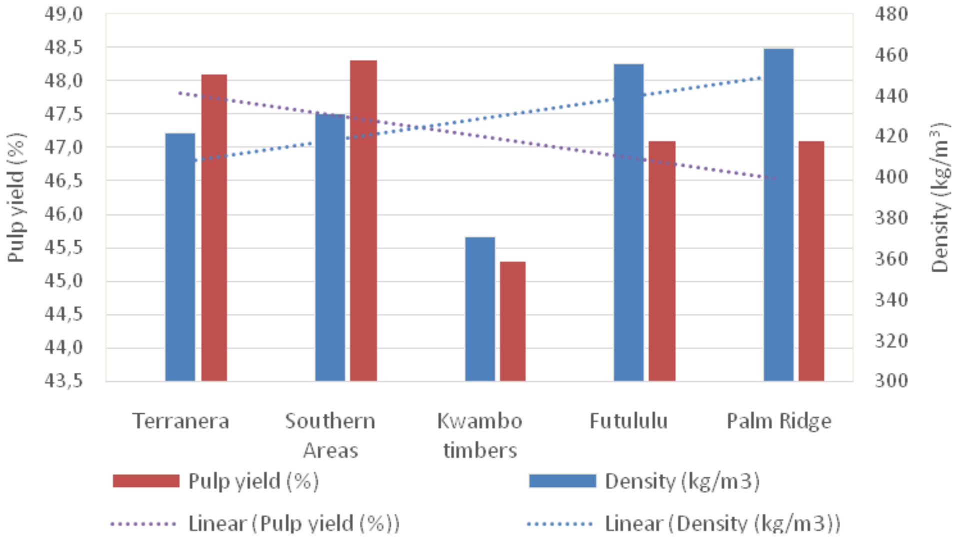

Figure 1: Variation in density (blue) and pulp yield (orange) for a single variety across 5 different sites.

These studies suggest wood property differences, driven by environmental variation within the same variety, can be as large as differences between varieties. There needs to be a better understanding of what drives this latter variation as all this wood is destined for pulping and the mill requirements are aimed at maintaining as uniform a fibre supply as possible. Moreover, it would greatly improve resource utilization if this type of variation could be better predicted.

Towards developing cost effective methodologies to assess wood property variation in standing trees

In a preliminary study, data was collected from several compartments across 4 species that differed in elevation and site quality. This included Resistograph measurements, sawdust samples for determining chemical traits and cores taken to measure actual densities. Mini plots were taken from each compartment as well as GPS co-ordinates. Initial results concur with the findings from the previous two studies. The same species planted in different areas (site qualities) had different densities, pulp yield and lignin content. The mini plots within a compartment also showed significant differences which indicate micro-site influences.

A vision for the future

In this paper, it is suggested that by using the understanding gained from these studies with that of the available technologies (such as near infrared spectroscopy and the Resistograph), it will be possible to develop a workable model to better predict fibre supply, based on a combination of genotype and environment. A better understanding of the variation infield would allow trees with similar fibre to be grouped together when being supplied to the mills. Alternatively, developing cost effective methodologies to measure wood properties, would at least allow forest practitioners to better map the variation with a plantation.

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EFFECT OF STAND BASAL AREA ON PONDEROSA PINE WOOD QUALITY: FINDINGS FROM A REPLICATED DENSITY EXPERIMENT IN ARIZONA, USA

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Introduction

Restoration treatments in the southwestern United States are currently generating large volumes of woody by-products. These are typically sold into low-value markets such as pallet stock (Lucas & Kim, 2016), if utilized at all. Meanwhile, contractors struggle with the high cost of operations relative to the low value of harvested material, therefore targeting higher-value products is essential. With this in mind, the aim of this study is to quantify and build models to predict the variation in important intrinsic wood quality characteristics of northern Arizona ponderosa pine *(Pinus ponderosa)* trees. Using destructive and non-destructive techniques, we assessed dynamic stiffness, static mechanical properties, and wood density of trees from six different stand densities. Our objectives were to 1) develop models for predicting mechanical properties of small clearwood specimens, and 2) develop models for the pith-to-bark variation in wood density.

Materials and Methods

Our study site (Taylor Woods) is a replicated 'levels-of-growing stock' experiment near Flagstaff, AZ, in which plots have been maintained at specified basal areas (6.9, 13.8, 18.4, 23.0, 27.5, or 34.4m^2ha^{-1}) by thinning every ten years (Bailey 2008). We selected 55 trees from 18 plots and measured their diameter at breast height, total tree height, canopy base height, and standing acoustic velocity. We then felled the trees and collected a bolt from just above breast height as well as 3-5 cm-thick cross sections at approximately 2.4-m intervals along the stem.

To address Objective 1, we processed each bolt into small clear mechanical testing specimens in accordance with ASTM D143(ASTM International, 2014). Each tree yielded between two and seven specimens, depending on its diameter. We assessed modulus of elasticity (MOE) and modulus of rupture (MOR) for each specimen on a Tinius Olsen 5000 Universal Testing Machine (Tinius Olsen, Willow Grove, PA). For Objective 2, we processed tree cross-sections into 2x5-mm radial strips mounted on 2 mm-thick hardwood strips. We used a QTRS X-ray densitometer (Quintek Measurement Systems, Knoxville, TN) to determine the wood density of the radial strip at 25-micron intervals.

We developed nonlinear mixed-effects models using the statistical program R (R Core Team, 2018). Mixed-effects models were necessary due to the hierarchical structure of the data (i.e. samples nested within trees), non-constant variance, and unbalanced data(Pinheiro & Bates, 2000). To satisfy Objective 1, we developed two models: one for MOE and one for MOR. Objective 2 analyses are currently being conducted and will be completed during summer 2018.

Results

A modified Michaelis-Menten equation with Rings per Inch, Ring Number, and basal area treatment provided the best fit to the data for both MOE and MOR. Moving from pith to bark, mechanical properties increased steeply at first before approaching an asymptote near the bark (Figure 1). Stands with higher levels of growing stock generally have higher mature wood values. Model fit statistics (Table 1) show that the models fit the data well, with the MOE model performing slightly better than the one for MOR.

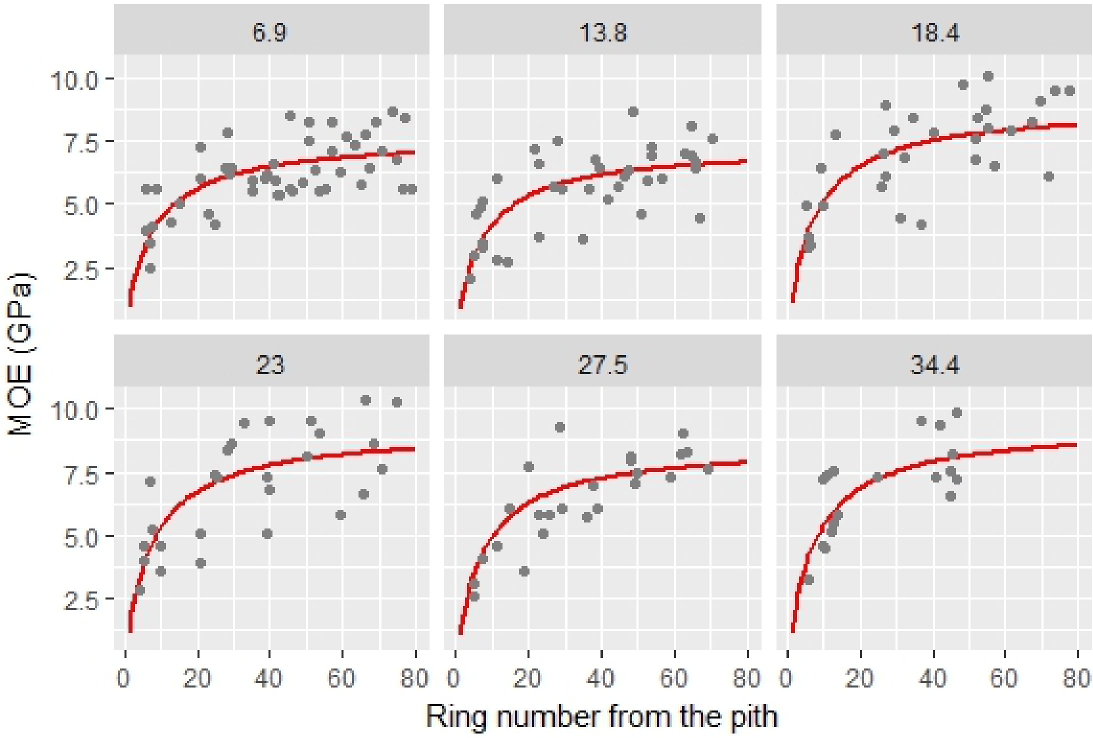

Figure 1: Scatterplot of Modulus of Elasticity (GPa) vs. Ring Number for the 6 basal area treatments (in m^2 ha^{-1}) at Taylor Woods. Observed values are represented by dots; lines show predicted values from the fixed effects of the Michaelis-Menten model.

Table 1 – Fit statistics, including pseudo-R^2(% variation explained) and model errors(Parresol 1999),calculated from the fixed effects of the MOE and MOR models.

Model	N	R^2	E	$\lvert E \rvert$	$\lvert E \rvert\%$	RMSE
MOE (GPa)	185	0.558	-0.004	0.963	15.710	1.186
MOR (MPa)	185	0.370	-0.565	9.543	14.637	12.105

Conclusions

In all trees, the same general trend was observed of rapidly increasing MOE and MOR near the pith that levelled off in the mature wood. Outside of the juvenile wood zone, wood properties compare favourably with those of other species that are used for structural lumber. The implications of this are that foresters and logging contractors in the southwestern US may be able to sell ponderosa pine restoration by-products in higher-value markets.

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THE LIVING STEM: AN INTEGRATED PHYSIOLOGICAL MODEL OF TREE STEM FORMATION FOR *PINUS RADIATA*

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Introduction

The mapping of wood properties in tree stems is an important challenge to determine the performance of wood products. To predict realistic distributions of wood properties in stems, it is necessary to operate across two physical scales by linking the tree to the fibre. Traditionally, process-based models have focused on either end of the spatial continuum for dendrochronology or ecophysiology purposes. Given the importance of timber production for planted forests, several models have been developed to bridge tree growth and wood formation (Drew and Downes, 2015, Fernández *et al.*, 2011, Deleuze and Houllier, 1998, Perttunen *et al.*, 1998). Elaborating on those models, we introduce The Living Stem (TLS), a simulation software of tree stem formation using a modelling approach based on local, distributed cambial activity so that production rate and properties of new wood material are spatially independent.

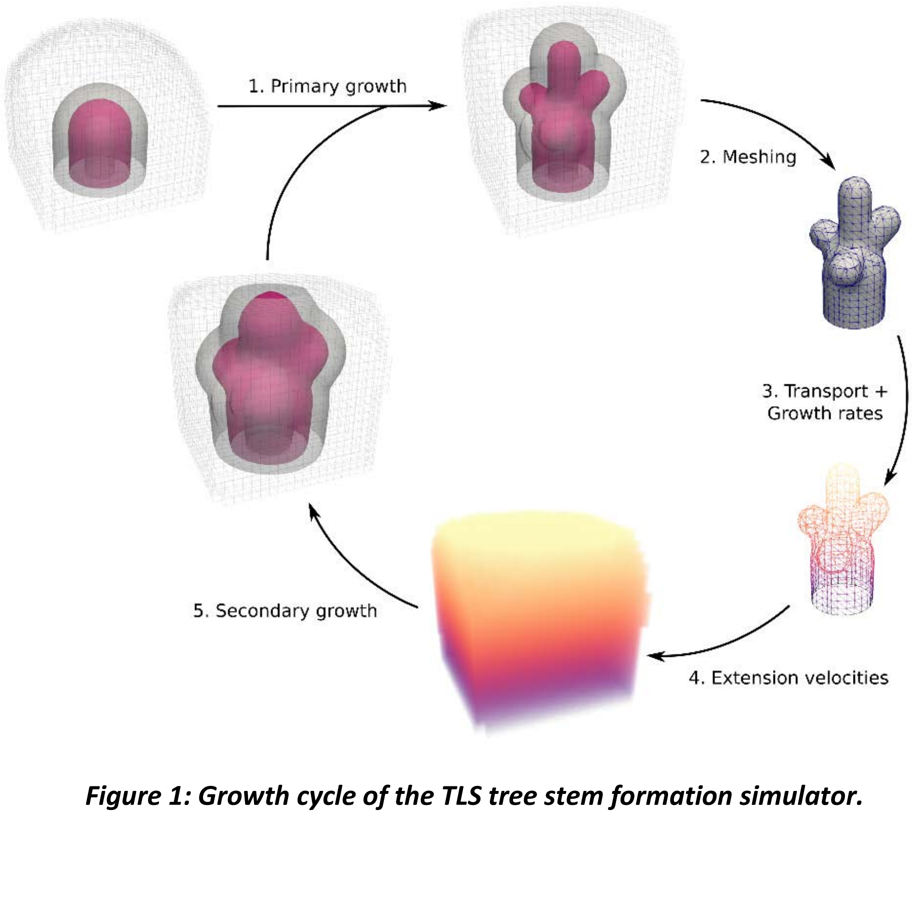

Figure 1: Growth cycle of the TLS tree stem formation simulator.

Materials and methods

The present model simulates the history of a tree stem development during a rotation period. Both the surface and the internal structure of the stem are described as three-dimensional objects. The central component of the model is a level set method (Sethian, 1999), which is a mathematical framework for surface growth problems, here adapted to describe the expansion of the cambial layer (Sellier *et al.*, 2011). Growth is defined by a speed function*(x,t)* that gives radial expansion rate depending on the position on the stem surface, *x,* and time, *t*. In this model, *f* is discrete as local growth rates are computed using multiple instances of a physiological model of wood formation, eCambium (Drew and Downes, 2015). In order to predict cambial production, eCambium requires information on local sucrose availability and xylem water potential. Those quantities are obtained globally for the tree using CaBala (Battaglia *et al.*, 2004); they are distributed on the tree surface using transport models of phloem and xylem sap flows (Sellier and Harrington, 2014).

Growth is simulated by replicating a cycle of successive steps (see Figure 1):

1. The stem surface is locally re-initialised to insert newly branched or elongated shoots
2. The surface is triangulated to a finite element mesh to model carbon and water transport
3. The growth speed function is evaluated at reference points on the surface.
4. The function is extrapolated to the level set computational domain
5. The surface is evolved to its next state. Loop to 1.

Results

The virtual tree stem was generated with TLS for a commercial Radiata pine forest of North Island, New Zealand (figure 2). The tree stem is compared with ones measured by destructive sampling.

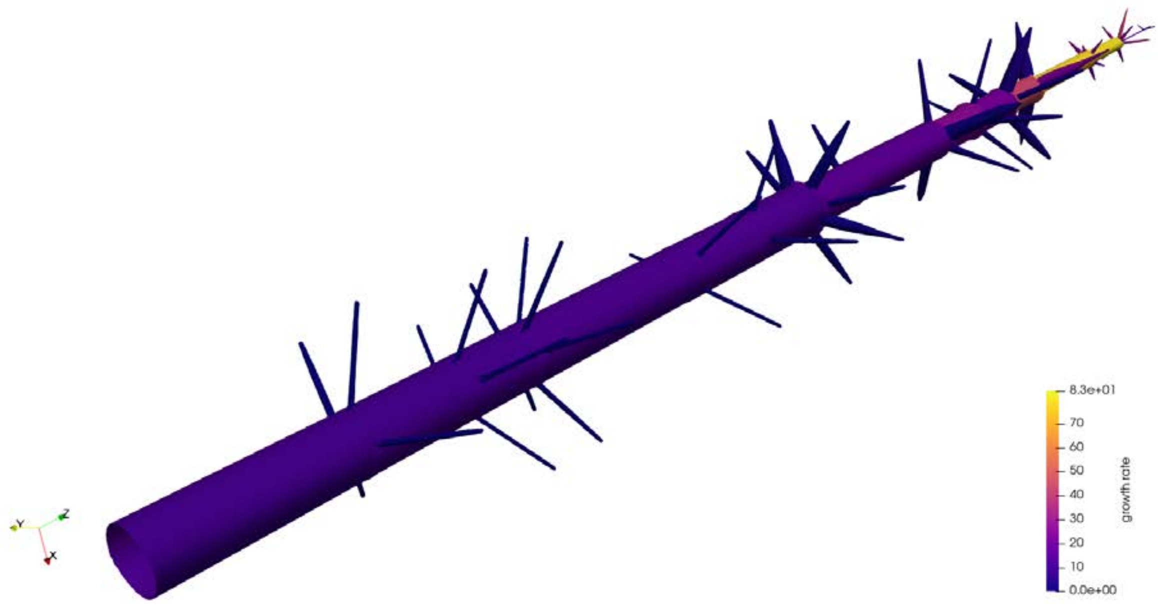

Figure 2: Stem surface and growth rates of virtual 3-year-old tree.

Conclusions

The present approach allows forecasting wood properties by generating high resolution volumetric maps while integrating the key physiological processes underlying tree development.

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LINKING KNOWLEDGE ABOUT GROWTH AND WOOD PROPERTIES IN RADIATA PINE – PAST, PRESENT AND FUTURE

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Introduction

Given the importance of radiata pine (*Pinus radiata* D.Don) to the New Zealand forestry sector, there has been a considerable focus on understanding growth and wood properties in this species. However, for many years research that focused on understanding and enhancing tree growth was not always linked with research into wood quality. Much of the initial work investigating radiata pine wood quality focused on quantifying the extent of variation in key properties of interest, principally density, within and among trees (Cown and McConchie, 1983; Harris, 1965;Palmer *et al.*, 2013), and how these were affected by forest management (Carson *et al.*, 2014; Cown, 1973; Cown, 1974; Cown and McConchie; 1981; Cown and McConchie, 1982). At the same time research into growth looked at how to improve both productivity and profitability. This has resulted in a reduction in rotation length and also silvicultural regimes that were often characterized by heavy and early thinning (James, 1990). The focus of much of the early tree improvement research was on enhancing growth and improving stem form, rather than on improving internal wood properties (Jayawickrama and Carson, 2000). Unsurprisingly, there have been concerns that many of these practices have had a negative impact on wood quality (Burdon, 2010; Cown, 1992;Moore and Cown, 2017). In order to better understand the implications of current and future research aimed at enhancing productivity on wood quality, better knowledge about the connection between tree growth and wood properties is required. In this presentation, we describe different modelling and experimental approaches that have aided our understanding of this connection.

Methods

Empirical models were developed to predict the radial and longitudinal variation in wood density, microfibril angle and spiral grain angle (Kimberley *et al.*, 2015; Moore *et al.*, 2014; Moore *et al.*, 2015) within a tree. These non-linear mixed effects models are based on ring-level data and account for the hierarchical structure in these data, which arises from the fact that they were obtained from radial samples taken at different heights in selected trees from a number of stands. The models enable the effects of ring number, ring width and height in the tree to be accounted for which enables them to be directly linked to growth models. In the case of wood density, genetic improvement can also be accounted for (Kimberley *et al.*, 2016).

This modelling approach is suitable for wood properties that are continuous and approximately normally distributed. However, traits such as resin pockets and intra-ring checks, which are major sources of value loss in appearance products (Cown *et al.*, 2011; Cown, 2013), are discrete and are better represented as counts. Previous efforts to try to describe the variation in these traits and the factors associated with their occurrence have generally not yielded many useful results. To identify factors associated with these traits, we have applied machine learning approaches, specifically Random Forests and Gradient Boosting Trees, to historical data on resin pockets and intra-ring checks.

Finally, we explore the potential to further link tree growth, form and wood properties through the analysis of high-density airborne LiDAR data acquired from a UAV, terrestrial LiDAR data and wood properties data that were obtained from a large (~10 ha) field experiment that contained a range of different seed lots and stand densities.

Results

Ring-level models have enabled the general intra-stem patterns in wood density, microfibril angle and spiral grain angle to be quantified. A large proportion of the radial variation in density and microfibril angle can be accounted for by ring number from the pith and ring width. This enables these models to be linked to growth models and used to predict the effects of factors such as age and stand density on these two wood properties.

At the time of writing, we have only just commenced the analysis of data on resin pocket and intra-ring checking occurrence using machine learning approaches, so do not have any results yet which identify any site, stand or genetic factors associated with the incidence of these two traits. Likewise, we have only commenced analyzing the LiDAR dataset that has been collected. We are currently calculating a range of stem and crown metrics for individual trees within this trial and will determine whether any of these are associated with wood density and stiffness measurements made on individual trees.

Conclusions

The simple empirical models that have been developed for radiata pine have enabled a better understanding of the effects of some growth-related factors on selected wood properties. However, such models do have a number of limitations. Firstly, they focus on associations rather than explicitly attempting to model the underlying growth and wood formation processes. Secondly, they still predict idealized patterns of intra-stem variation in wood properties and ignore the departures from this pattern due to factors such as the presence of reaction wood. More realistic representations of these patterns is needed in order to better understand the impacts on end product performance.

It is hoped that being better able to characterize the growing environment of a tree and its crown structure will lead to an improved understanding of the connection between tree growth and wood properties.

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POSTER PRESENTATIONS

A MODEL TO ESTIMATE LEAF AREA INDEX IN LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST UNITED STATES USING GROUND BASED MEASUREMENTS AND SATELLITE DATA

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Introduction

Leaf area index (LAI) is an important indicator of a stand's productivity as it measures the stand's ability to exchange material and energy with its environment and has been shown to maintain a positive relationship with biomass production (Grier and Running, 1977; Albaugh *et al.*, 1998).LAI, the one-sided leaf surface area over a fixed ground area, has been shown to be responsive to nutrient and water amendments on limited sites in the south-eastern United States, signalling its importance in reflecting the productivity of site conditions (Albaugh *et al.*, 1998). Methods for estimating leaf area index include destructive sampling, hemispherical lenses, models for remotely sensed data, or use of plant canopy analysers, such as the Li-Cor 2200 (Peduzzi *et al.*, 2002). Prior models that utilize satellite imagery to estimate leaf area index of a site have been put forth but were shown to be biased, underestimating leaf area index (Flores *et al.*, 2006). Advances in satellite image processing have allowed for consistent geometric and radiometric calibration for new and historic imagery, easily allowing for cross sensor comparisons to be made for times series observations. The objective of this study is to develop an unbiased model that estimates LAI for loblolly pine plantations in the south-eastern United States from Landsat 5 and 7 derived vegetation indices.

Materials and methods

The site used for this study comes from The Southeast Tree Research and Education Site (SETRES) located in the sandhills of North Carolina where a combination of fertilization and irrigation treatments were applied to eight-year-old loblolly pine trees (Peduzzi *et al.*, 2002). LAI of each treatment plot was estimated using a Li-Cor LAI-2000 Plant Canopy Analyser on a monthly interval from March 1992 until September 2004 (Sampson *et al.*, 2003). Using the Google Earth Engine platform for data access, surface reflectance values were queried and extracted from Landsat 5 and 7 images for field sites matching the date range of field measurements. A variety of vegetation indices were calculated for testing. Due to satellite observations not matching the exact date a field measurement was taken, the four closest satellite observations before and after the matched field measurement were fitted to a cubic spline and a value was predicted for the field measurement observation date. A model was fitted to the best fit vegetation index when compared to the in-situ leaf area index measurements. Due to the within year dynamic nature of leaf area index, simulated extrapolation was used to account for noise in our dependent variables.

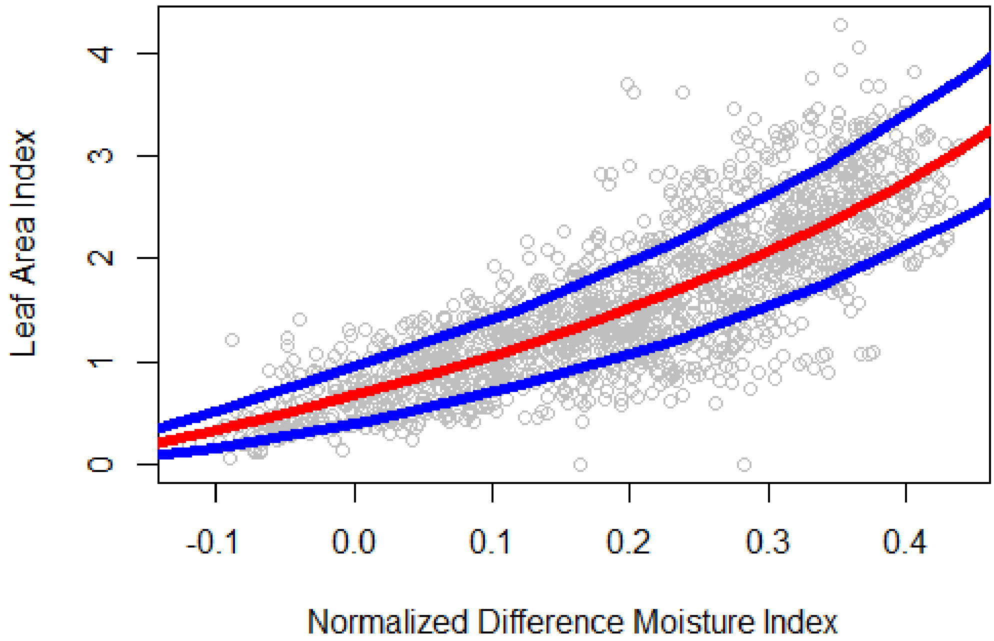

Figure 1: Relationship between calculated vegetation index from Landsat 5 and 7 data and observed leaf area index values.

Results

Our early results show good agreement between ground-based estimates and satellite data. Normalized difference vegetation index (NDVI) was found to be weaker as a LAI predictor as compared to the normalized difference moisture index (NDMI) (AIC =2587.4 vs. 1885.8). The two comparisons had large errors, and a very weak correlation between their first order differences. Nevertheless, an equation was fitted to account for the uncertainty in LAI prediction.

Conclusions

Our models show good agreement with the accumulated LAI behaviour in spite of the large errors shown at each regression. Practitioners can make use of these equations provided an understanding of the risks associated with the estimates.

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PREDICTING INDIVIDUAL-TREE GROWTH USING STAND-LEVEL SIMULATION, DIAMETER DISTRIBUTION AND BAYESIAN CALIBRATION

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Introduction

Individual-tree models are flexible but also very time and data demanding. At least two time points of individual-tree measurements are necessary for developing diameter growth, survival and ingrowth models. Permanent plot data match the data demanding of growth models, but it may take several years to obtain the necessary data. Even though individual tree models can be developed using temporary plots data, tree cores are generally not available for most forest management inventories.

The purpose of the present paper is to develop an individual-tree model of *Pinus tabuliformis* (Chinese pine) with limited temporary plot data. We propose an approach to generate adequate virtual data for fitting individual-tree growth models by linking stand- and size class-level simulations. First, to predict stand dynamics at the stand level based on empirical data; second, to simulate diameter distribution using Weibull function with observed size class-level data; third, using the simulated data to fit individual-tree models with Bayesian calibration on a likelihood of diameter distributions. All the modelling data in the study were collected from temporary plots. A relatively adequate dataset of tree cores was also obtained, but only for the validation of our virtual data based modeling method.

Materials and methods

The data for developing the models were collected from 215 variable radius plots and 22 fixed 0.04 ha square plots established in *Pinus tabuliformis* plantations. The data were provided by the forest management planning inventory (1990, 2005, and 2015), which is level Ⅱ forest inventory in China (Lei *et al.*, 2009).

The model development implied 3 steps:

(1) Development of a whole-stand model that estimates stand average height, basal area per hectare, and quadratic mean diameter, fitted by temporary plots data. This whole-stand model simulates the developments of stand-level attributes of 30 virtual one-hectare plots from age 20 to age 80, which were on 6 site classes and 5 kinds of initial density (6*5=30 plots).

(2) A moment-based parameter recovery Weibull distribution (Cao, 2004) was adopted to simulate the diameter distribution. The diameter distribution model simulates the diameter distributions of virtual plots for each 5 years.

(3) An individual-tree model simplified from Pukkala *et al.* (2009) was fitted using Bayesian calibration and simulated virtual data. A special likelihood function modified from Pukkala *et al*. (2011) was used for fitting individual tree models to solve the identification problem.

Results

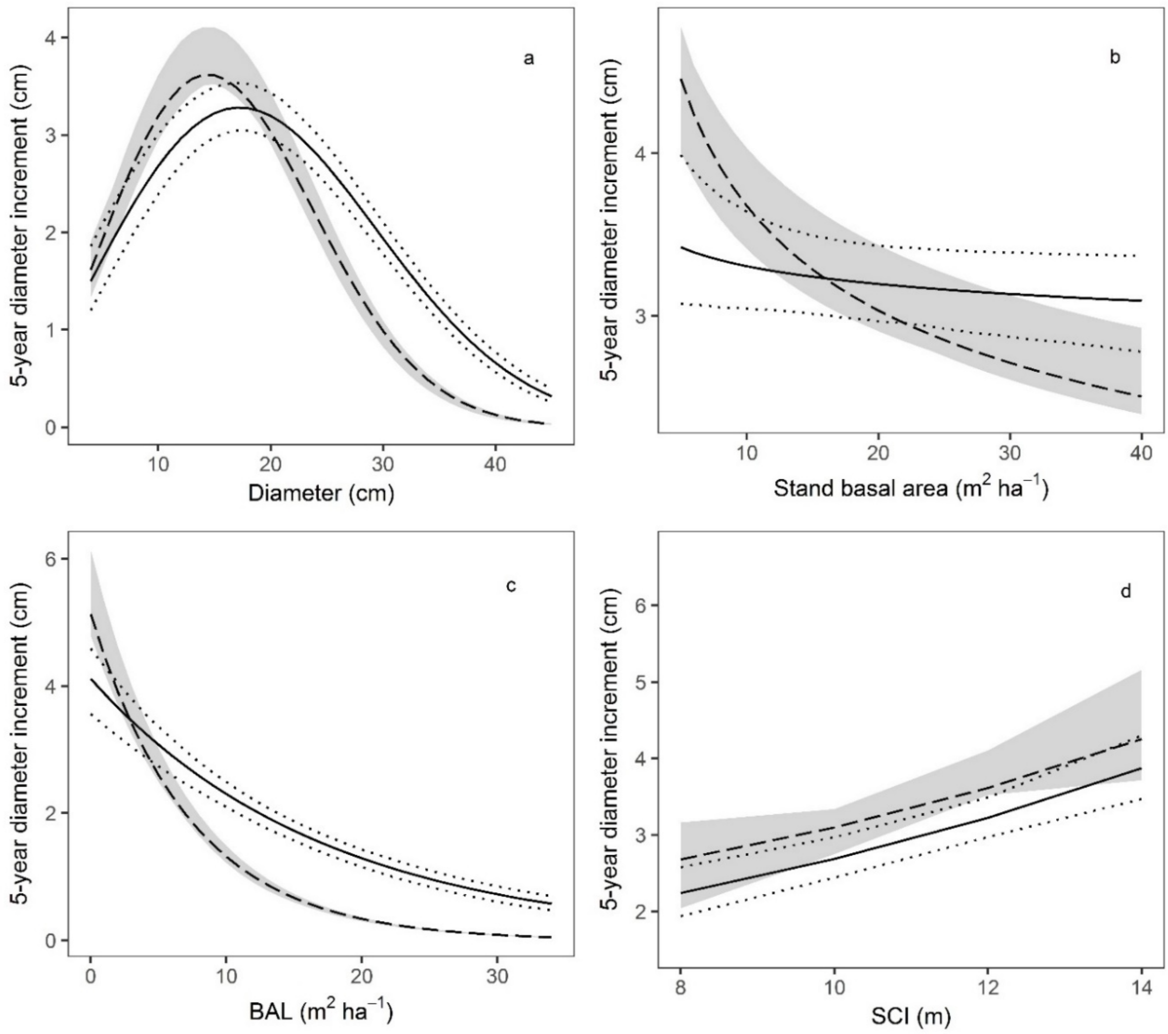

Figure 1 Comparison of individual-tree diameter increment predictions based on simulated virtual data and increment cores approach. Fig 1a, 1b, 1c, 1d are, respectively, the relationships of 5-year diameter increment over diameter, stand basal area, basal area of larger trees, and site class index (average height on the reference age). The dashed line and solid line are, respectively, virtual data based predictions and increment core method predictions, which are generated by MAP (the maximum a posterior parameter vector). The grey area and dotted line, respectively, represent the 95% Bayesian credible interval based on parameter uncertainty of virtual data method and increment core method. For Figure 1a, the stand total basal area is 25 m^2 ha^{-1}, the basal area of larger trees is 5 m^2 ha^{-1}, and the site class index is 12 m. For Figure 1b, the diameter is 20 cm, the basal area of larger trees is 5 m^2 ha^{-1}, and the site class index is 12 m. For fig 1c, the diameter is 20 cm, the stand basal area is 35 m^2 ha^{-1}, and the site class index is 12 m. For fig 1d, the diameter is 15 cm, the stand basal area is 20 m^2 ha^{-1}, and the basal area of larger trees is 5 m^2 ha^{-1}.

Conclusions

We validate this cheaper method for individual-tree level growth modelling with data collected from increment cores. They have the same pattern and similar performances. Meanwhile we used a regression-based equivalence test of Robinson *et al*. (2005) to benchmark all the three resolution models. Stand-level basal area model showed the best performance in both intercept and slope tests. Since the area of the fixed square plot is only 0.04 ha, random errors of Weibull distributions were largest when compared with observations. Equivalence tests for individual-tree diameter increment model also largely failed to reject null hypotheses of dissimilarity, showing underestimation of the growth for the suppressed trees.

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MODELLING FOREST ATTRIBUTES ACROSS SCALES USING A HIERARCHICAL APPROACH: ACHIEVING GAINS IN INSIGHT WITHOUT GETTING LOST IN THE COMPLEXITY

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Introduction

Forests are complex systems within which intricate linkages exist at multiple spatial and temporal scales. Accordingly, while questions are often asked at one scale (e.g. what is the wood density in the juvenile core of this tree?), robust answers may require analysis/perturbation at other scales (e.g. how does stand management or landscape position influence or determine the outcome of interest?). Scientists, however, may not always have the data, or a sufficiently detailed understanding, to capture all the complexity in comprehensive, fully integrated models that span scales from the lowest to the highest resolution. In an attempt to develop models to predict and generalize patterns of tree growth, timber yield, or other outcomes from forests, modelers must usually make a decision at which scale to focus their thinking. It is certainly feasible to develop realistic, accurate and hopefully adequately generalizable models that operate within fairly strict spatiotemporal limitations. What opportunities are there, however, to link distinct models at these various scales in a hierarchical fashion, so that the benefits required at each scale can be derived without "getting lost in the complexity"?

We explore here various aspects of this question. We look at how linked modelling solutions involving the transfer of applicable variables across differently scaled models can provide a means of predicting final expected outcomes in ways that are tractable and accessible.

Review of approaches

We provide a review of some recent research where authors have adapted existing approaches, or developed new frameworks for utilizing outcomes/variables predicted at one scale (often the stand level)to hierarchically predict a new set of outcomes at a finer scale (spatial and/or temporal) with distinct, often independent models. Models that take this approach are both empirical and process-based types. We focus on two broad groups, consisting of both types. First, models that initially model at the stand scale and then use emergent stand-scale properties to hierarchically model tree level variables. Second we look at approaches that initially model stand or tree-level variables, and then hierarchically model within-tree properties, such as branching, or pith-to-bark wood properties. We give consideration here also to error propagation as it pertains to an increase in resolution, and to the importance of compatibility and inter-relatedness between what are often simultaneous models running at various scales.

Three case studies

We then focus on the benefits derived from a hierarchical approach in three case studies that used linked processed-based models with an initial simulation at the stand-level. The three instances we discuss took a hierarchical approach to (a) predicting mortality within stands (Battaglia *et al.*, 2015), (b) modelling damage from plantation pests (cf. Pinkard *et al.*, 2017) and (c) modelling within-tree wood property variability (Drew and Downes, 2015).

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MODELING ABOVE-GROUND STEM VOLUME AND TREE BIOMASS FOR *SEARSIA LANCEA* (L.F.) F.A. BARKLEY IN CENTRAL BUSHVELD, SOUTH AFRICA

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Introduction

Forests and woodlands are major renewable resources which can provide a wide range of economic, social and environmental benefits (FAO 2010, Chidumayo *et al.*, 2011). Above-ground biomass and stand volume are the two main measures of forest stocking (Brown 1997, Brandeis *et al.*, 2006), which are used in different ways for various products (Geldenhuys and Kruger, 2016). Forest biomass is becoming an essential ecological variable in ecological research for understanding potential future changes of the climate system as well as to gauge the true production potential (GTOS, 2009).*Searsia lancea,* commonly known as Karee, has numerous benefits, including branches as fodder (Venter and Venter, 2009; Woolley *et al.*, 2011), wood as termite-proof posts (Van Wyk and Gericke, 2000), and for bio-energy purposes (Geldenhuys and Kruger, 2016). However, models are lacking for estimating stem volume and tree biomass. Applying generalized equations is problematic because they may result in biased estimates for some species (Chave *et al.*, 2005, Tesfaye *et al.*, 2016). As a result, the aim of this study was to estimate stem volume and tree biomass per hectare and to develop tree biomass and stem volume models based on destructive harvesting.

Materials and methods

The Karee dominated woodland on the farm of Kusala Green and Biodiversity Organization (KGB), between Brits and Marikana in North West Province of South Africa, was selected for the study. A stratified random sampling was done, by selecting two blocks with both sparse and dense Karee stands. In each block, three sparse and three dense Karee stands were identified. Within each block, three thinning treatments of only Karee stems (no thinning, 50% thinning and 100% clear-felling) were randomly allocated to the selected stands. On each circular plot, all trees with stem diameter at breast height (DBH) of ≥5 cm were recorded by tree number, stem diameter and species. Subsequently, each felled tree (DBH ≥5 cm), from both 50% and 100% treatments, was partitioned into crown (twigs, leaves and small branches with a branch diameter <5 cm) and large branches (branch diameter ≥5 cm) to determine their fresh/green weight. Sub-samples (short stem sections/disc samples around 10 cm long of 12 stems of Karee) were collected from the harvested stems and branches for the determination of their fresh weight in the field and dry weight in the laboratory. The samples were then oven dried at 70^0C until constant weight was attained. Consequently, the ratio of sub-sample dry weight to fresh weight was then used to convert component fresh weight to dry weight. Total tree biomass of a tree was computed as the sum of each component (Mugasha *et al.*, 2013). Mid diameter and length of each stem section were used to calculate the volume of individual sections using Huber's formula (Loetsch *et al.*, 1973), and the sum of each section volume was used to calculate the total volume of a stem. Total tree biomass and stem volume per hectare were calculated for both stands.

A total of 110 stems from eight plots were used for developing tree biomass and stem volume models. Only complete stems were selected to represent a range of diameter classes or stem sizes. Then, total tree biomass and stem volume as response variables and DBH and stem length as predictor variables were used to develop the models. This study aimed to select two candidate models, i.e. one with DBH only and the other with both DBH and height, in order to compare and select the very best one. Coefficient of determination (R^2), residual standard error (RSE) and residual mean squared error (RMSE) were used as model performance metrics (Kuyah *et al.*, 2016). Akaike Information Criteria (AIC) was used as final criteria for selection of the best model in which the model with lower AIC was selected (Chave *et al.*, 2005; Mugasha *et al.*, 2013). Finally, the best models were used to estimate tree biomass, stem volume and carbon stock of Karee stands.

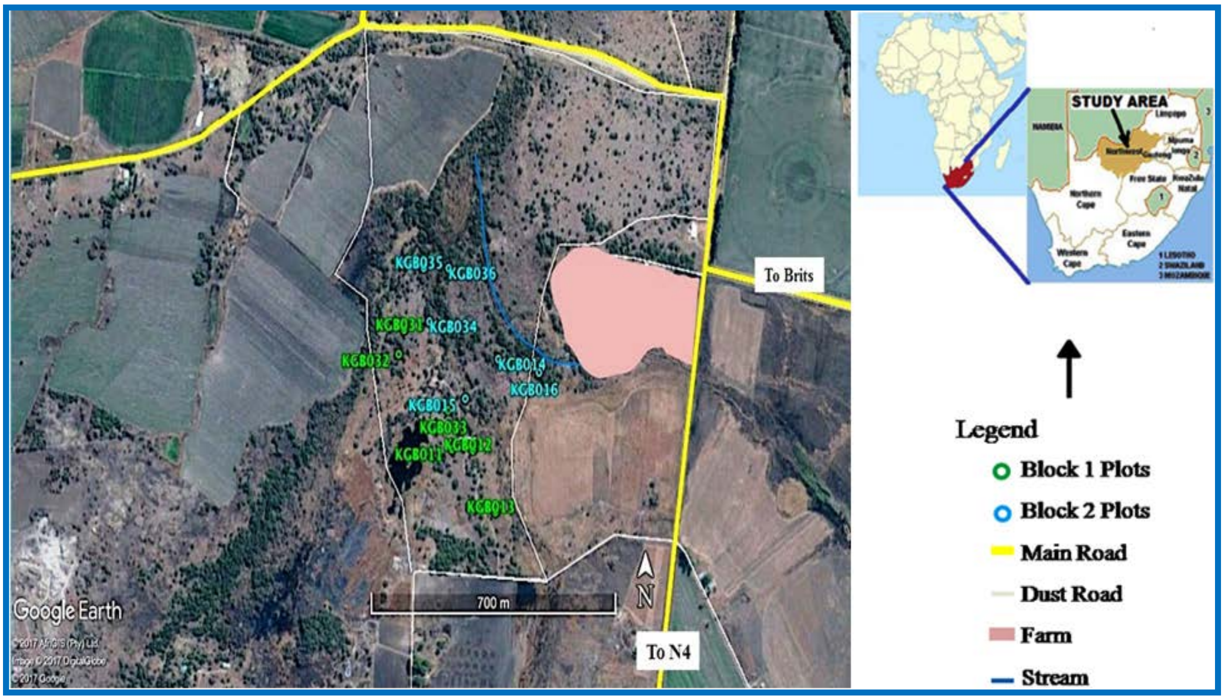

Figure 1: Location map of the study area

Results

A 50% thinning in sparse stands produced a stem volume of 11.92±6.28 m^3ha^{-1}; and total dry biomass of 8.51±3.63 t ha^{-1}; and in dense stands it produced a stem volume of 22.97±4.38 m^3 ha^{-1}; and total dry biomass of 16.05±2.42 t ha^{-1}. The clear-felling (100% thinning) in sparse stands produced a stem volume of 14.10±4.01 m^3 ha^{-1}; and total dry biomass of 10.02±4.48 t ha^{-1} and in dense stands, it produced 60.64±22.97 m^3 ha^{-1}; and 33.80±2.25 t ha^{-1}. Models were then developed by using 110 destructively harvested stems by regressing stem DBH and length with stem volume and tree biomass.

Conclusions

Biomass plays an increasingly important role in society. There is no doubt now that energy is fundamental to development. This study unveiled the potential value of the species to produce wood chips and/or pellets for use as bio-energy by estimating the contribution of tree biomass and stem volume per hectare. A set of prediction models were developed for Karee to estimate the total above-ground stem volume, tree biomass and carbon stocks from stem diameter and stem length/height. These models can be used by interested organizations for research and other purposes. Therefore, promotion of the management of such woodlands will reduce the risk of loss of biodiversity while enhancing carbon stocks, thus shedding light on the implications for REDD+ (Reducing Emissions from Deforestation and Degradation) schemes. In this regard, Karee can be used as a potential energy source (with lower carbon release to the atmosphere) by producing pellets for use as bio-energy, which can help to alleviate the problems of energy, while also increasing carbon stock. These results combined with future studies can be used to develop future guidelines for sustainable harvesting of Karee species in the woodland for bio-energy, fuelwood and other purposes.

Key words: multi-stemmed, Karee, stem diameter, stem length, stem thinning, clear-felling, tree biomass, stem volume, bio-energy, carbon.

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CHANGES OF AERIAL BIOMASS ALLOCATION IN *PINUS RADIATA*, MEDIATED BY COMPENSATORY MECHANISMS AFTER SILVICULTURAL TREATMENTS

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Summary

How does the aerial biomass change after the application of pruning and thinning? Does any mechanism exist at tree level that compensates for loss of biomass? The present work studies the aerial components of *Pinus radiata* trees and stands under silvicultural treatments, in the southeast of the Province of Buenos Aires Argentina. In a 10 years old trial with different management schemes: *control, thinning, pruning and thinning*, thinning increased the incidental light intensity on needles and branches, strengthening its production in the remaining branches left by pruning. The relationship needles /branch biomass was 0.48 in the *pruning and thinning* treatment, and significantly different ($p < 0.05$) to *control* (0.30) and *thinning* (0.28). The increase of leaves biomass in upper and illuminated branches suggest a compensatory mechanism that allow for relatively stable relationship between needles, biomass, and the area of conductive tissue of the stem as proposed by the pipe model theory.

Key word: needles biomass, branch section, pruning, thinning.

Introduction

The purpose of silvicultural treatments is to increase the productivity of intervened stands. When forest management is oriented to the production of knot-free wood, it is expected to concentrate the growth on a few trees of good size, shape and with the least possible number of defects. To do that, it is necessary to adjust the combination of silvicultural treatments intensity and opportunity, according to quality site (Gerding, 1991; Trincado and Burkart, 2009; Groot and Schenider, 2011; Fernández *et al.*, 2017). This can cause changes in the partition and distribution of the biomass produced. The theory of the pipe model proposed by Shinozaki *et al.* (1964 a, b), postulates that there is a relation of proportionality between the leaves of a tree and its conductive elements. The objective of this study was to evaluate the effect of different silvicultural pruning and thinning treatments on the allocation of aerial biomass in individual trees of *Pinus radiata* in the context of this theory.

Material and methods

The study was carried out in the Southeast of the Province of Buenos Aires, Argentina, on a trial whose geographic coordinates are: 37° 33´ 34,71" S y 59° 07´ 50,96"O. The stand was planted in 2001 at a stand density of 1111 trees ha^{-1}. The applied treatments were: *control* (without intervention), *thinning* (50% thinning at 6 years), *pruning and thinning* (50% thinning at6 years, with 3 pruning 40% at 6, 7 and 9 years).

A destructive analysis of four trees by treatment was carried out. For stem biomass, the selected trees were cut, their stem volume was obtained using Smalian equation, the wood density of each stem section was measured and the stem weight was calculated. Wet needle and branches of each whorl were weighted separately, and a subsample was oven dried at 60 ° C until a constant weight was achieved. Using the percentage of dry matter, the dry weight of each branch (kg) and the dry weight of leaf biomass per branch (kg) were obtained. A second-grade equation was adjusted to each treatment, between tree height and the ratio needles biomass / branch cross section area.

Results

No significant differences (Figure 1) were found between treatments in the relationship between tree height and the ratio needles biomass / the cross section area of branches. However, when analyzing the relationship between needles biomass and branch biomass (Figure 2), the treatment of *pruning and thinning* showed significant differences with respect to the remaining treatments.

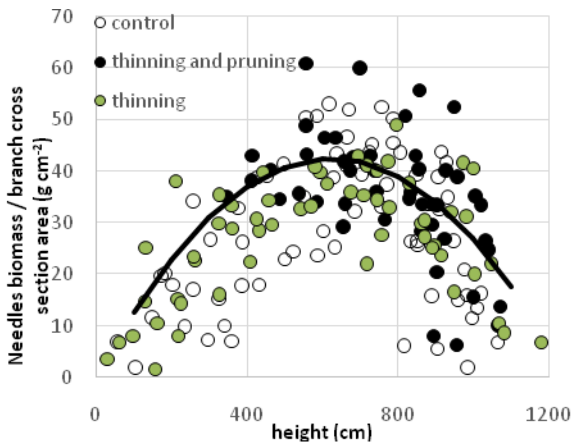

Figure 1. Rationeedles biomass/branch cross section) as a function of tree height

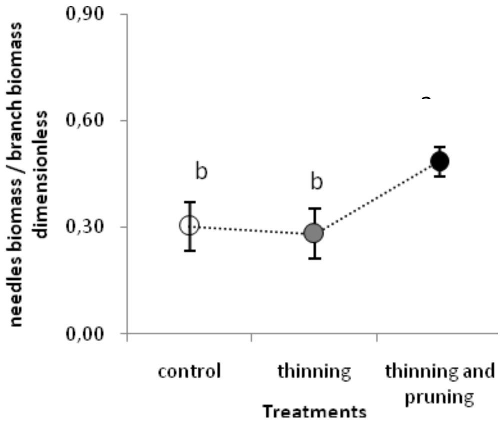

Figure 2. Ratio Needles biomass/branch biomass by treatments. Different letters denote statistically significant (P < 0.05) differences.

Conclusions

The present study shows that for this species and under the trial conditions there is a relatively stable relationship between the biomass of needles and the conductive area of branches, which is expressed independently of silvicultural management. However, in the treatment of pruning and thinning, evidence on a scale of branches of the existence of a compensatory mechanism was found, as suggested by Ares and Brauer (2005). This consists of an increase of the amount of leaf biomass in relation to the branch biomass.

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ALLOMETRIC MODELS FOR ABOVEGROUND BIOMASSOF EUCALYPTUS GRANDIS X NITENS

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Introduction

The carbon sequestration potential of forest ecosystems, including industrial plantations, is becoming increasingly appreciated. The quantification of this ecosystem service aids industries in their compliance to new, incoming legislation and protocols surrounding climate change policies. Quantification of sequestered carbon pools in forests calls for tools that accurately predict biomass and carbon stored in it. The modelling of tree biomass components from allometric relationships between tree biomass components and easy-to measure variables are able to accurately predict tree biomass. This study developed a set of robust specie-specific biomass models for the *Eucalyptus grandis* x *E. nitens* (E. g x n) hybrid, an important variety for pulp production in South Africa.

Materials and methods

Six E. g x n sites were chosen used for this study. Three of the selected sites are planted with a single variety (an important variety which makes up 50% of the E. g x n) ("A") and each of the other three sites had a different E. g x n variety ("B", "C" and "D"). Within the two variety groups ("A" and "other"), three site class categories were selected based on existing plantation inventory data. At the "A" sites, 12 trees were sampled at each site, while 4 trees were sampled from each of the sites ("B", "C" and "D"). Full fresh weight was determined for foliage, branches and stems for each sampled tree. Dry weight was subsequently determined using standard methodology in the laboratory for scaling. A set of candidate biomass models were fitted to the data, using multiple fitting techniques, and parameters estimated. Biomass expansion factors were calculated, and an approach developed to take into account the effect of age. Foliar nutrient analyses were undertaken to determine potential nutrient export from the sites.

Results and conclusions

A common set off models using only Diameter at Breast Height (DBH) and total height are recommended for use based on general fit, parsimony, ease of use and additivity. The use of maximum likelihood, as opposed to least squares techniques for fitting was found to be an elegant approach. It was found that the development of separate models for different site productivity classes is not warranted when using the recommended model or models using DBH alone. The average above ground biomass per hectare calculated through upscaling from tree to stand level was 137 ± 34 T·ha-1 with a biomass expansion factor (scaling from stem wood biomass to total above ground biomass) value of 1.22. Relating allometric differences to developmental stage allows for the development of an age modifier for biomass expansion factors, allowing for the prediction of above ground biomass of stands at any age. The study also reports on nutrient concentrations of biomass components of the *Eucalyptus grandis* x *nitens* resource, with estimates of up-scaled total nutrient content. This is important because the forestry industry requires an estimate of nutrient loss for various management scenarios to manage plantations sustainably. Providing evidence of sustainable practices grants access to markets regulated through certification bodies. The data produced in this context based on newly developed biomass functions contributes to the assessment of sustainable site management practices. Also, managing plantations sustainably is ethical and ensures continued timber supply through the maintenance of soil fertility.

REFINING THE PARAMETERIZATION AND STRUCTURE OF A CLIMATE-GROWTH MODEL OF BOREAL FOREST

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Introduction

PREBAS is a semi-process-based combination of models of climatic factors and tree growth, namely PRELES and CROBAS, respectively (see Table 1 for parameters). Focussed on the light use efficiency (LUE), PRELES predicts daily GPP (P_k, kgC m^{-2} d^{-1}) along with other traits of a given forest by minimal counts of input data (Mäkelä *et al.*, 2008; Peltoniemi *et al.*, 2015; Minunno *et al.*, 2016).The yielded P_k functions as a fundamental to the second model, i.e. CROBAS, which describes tree growth centred on the acquisition and allocation of carbon (Mäkelä, 1997; Valentine & Mäkelä, 2005). Originally, PREBAS was calibrated with data of the boreal forests in Southern Finland, which thus would face challenges in arctic application. The current study shows and compares the results of the original, re-parameterized and structurally refined versions of PREBAS on a case in East Finnish Lapland. Its broader use and disentangling uncertainties is under ongoing research.

Materials and methods

Field data were collected on *Pinus sylvestris*, *Picea abies* and *Betula pubescens* from study sites at the Värriö Research Station in North-eastern Finland with meteorological data of the vicinity (Figure 1). The data of young trees (<70 a) are set as initials in order to compare the results of simulations of original, re-parameterized and structurally adjusted PREBAS to the actual data of old trees (≥70 a).

Figure 1: Location of the Värriö Research Station in Finland with tomography shown by colours (map source: Paikkatietoikkuna)

Table 1. Adjusted parameters of the CROBAS model. Note that the ones that remain their original values through this study are not listed.

Name	Meaning	Note*
P_0	Maximum annual photosynthetic production of stand	P R_M
$\nu_{F,ref}$	Leaf longevity (a)	R_C
ν_R	Fine root longevity (a)	R_C
k_H	Homogeneous extinction coefficient	R_C
s_{LA}	Specific leaf area (m^2 kg^{-1}C) (all-sided)	R_M
α_{Rs}	Ratio of fine roots to foliage	R_C
z	Foliage allometry parameter	R_M
c_R	Light level at crown base that prompts full crown rise	R_M
ϑ_{max}	Maximum ϑ, which is a term of disproportionately conversion of sapwood to heartwood dependent on tree age	S
t_0	Start age of secondary growth	S
γ	Rate of change of ϑ from 0 (at t_0) towards ϑ_{max}	S

*Notation: P – yielded by PRELES; R_M, R_C – re-parameterized by measurements or citation, respectively; S – newly hypothesized in structure.

Yield of $P_0$from PRELES:

$$P_0 = \sum_{k=1}^{365} P_{0k} = \sum_{k=1}^{365} [\beta f_S(S_k) \times f_\Phi(\Phi_k) \times \min\{f_D(D_k), f_\theta(\theta_k)\} \times f_{APAR}]$$

where $f_{S,\,\Phi,\,D,\,\vartheta}$ are modifiers of temperature, photosynthesis, vapour pressure, and soil water, respectively; subscript *k* denotes day of year (DOY); and is a site-specific parameter.

In the original CROBAS, the dynamic of sapwood area at breast height (*A*) is expressed as

$$\frac{d(A^+ - A^-)}{dt} = z\frac{A}{L_C}\frac{d(H - H_C)}{dt}$$

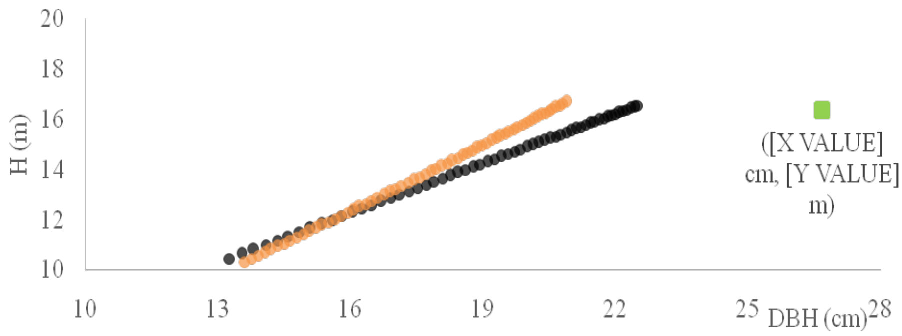
being a proportional relationship. However, faced with overestimation of *H* of aged trees with regard to D_{13}, it is now hypothetically modified to

$$\frac{d(A^+ - A^-)}{dt} = z\frac{A}{L_C}\frac{d(H - H_C)}{dt} + \vartheta A$$

and

$$\vartheta(t) = \frac{\vartheta_{max}}{1 + \exp\,[-(t - t_0)\gamma]}$$

One example of results



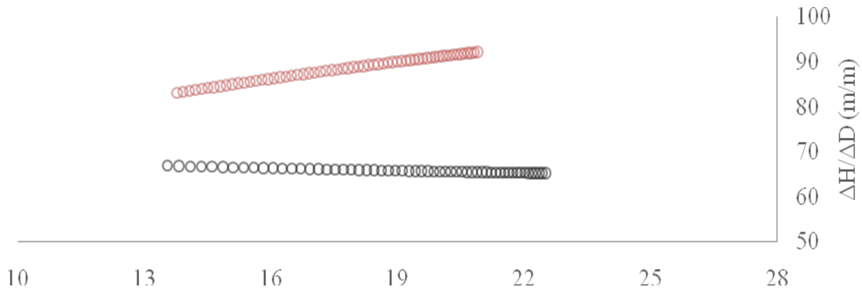


Figure 2: Simulated 61-year growths of height (H; m) and diameter at breast height (DBH; cm) of 37 young Scots pines (Pinus sylvestris; mean age = 60) in one 0.1-ha plotat the Värriö Research Station by original (red solid circles) and re-parameterized PREBAS (black solid circles). Empty circles are yearly changes of H-D ratio (ΔH/ ΔD; m/m); colours mean the same as for the solid ones. The green solid square is a reference of the means of measured dimensions of 23 old Scots pines (mean age = 121) in the same plot.

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EXTRACTION OF NON-COMMERCIAL FOREST PLOTS DYNAMIC CHANGE BASED ON OBJECT-ORIENTED CLASSIFICATION IN YANQING AREA

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Introduction

Classifying land-use type, extracting information and monitoring dynamic changes using remote sensing data is a very relevant research field nowadays. Monitoring the dynamic change of non-commercial forest is of great significance to forestry development in China, due to the importance of this forest type. Based on GF-1, RapidEye and Spot-5 images of Yanqing District, pix-based and object-oriented classification methods were used to choose the optimal approach for change detection. On the basis of object-oriented classification, optimal multi-segmentation scale and establishment of rule set were studied to improve the classification accuracy. Furthermore, through analysing the results of change area, this research would provide tactical reference and suggestion for non-commercial forest monitoring system.

Materials and methods

Materials

The study area lies at Yanqing District, Beijing, North-East China (40°16'~40°47'N, 115°44'~116°34'E), representing the typical non-commercial forest zone under the “Converting cropland to forest” Project. The material used in this study consists of 3 sets of satellite data which cover the whole research area (approximately 199 thousand hm2) and 3 sets of Forest Management Planning Inventory data (FMI data). The satellite data was provided by the Research Institute of Forest Resource Information Techniques and the FMI data was provided by the State Forestry Administration.

Methods

To obtain an optimal method for image enhancement of Spot-5 and GF-1 data, 5 frequently-used methods were used: hue, saturation, and value (HSV); Brovey transformation; Gram-Schmidt spectral sharpening; Principle Component (PC); and Pansharp transformation (Lin Li *et al.*, 2014; Zhixiong Gao, 2015). Qualitative and quantitative analyse were used to access the effect and quality of the fusion images.

Based on the fusion images, three pix-based classification methods were applied to extract non-commercial forest. In addition, as a contrast, object-oriented classification was applied to images based on multi-scale segmentation and rule set system (Haralick *et al.*, 1973; Ketting *et al.*, 1976; Jyothi B N*et al*., 2008). In this method, object-oriented ratio of mean difference to neighbours to standard deviation (RMAS) (Yongguang Zhai *et al*., 2010; Johnson B. *et al*., 2011) and mean value index (Drăguţ *et al.*, 2010) were used to set the optimal segmentation scale. In addition, dichotomy model was introduced to object level from pix level and the FC value was added to the rules to realize the object-based classification. By using the method of comparing the classification results (Ni Wang, 2012), change information was extracted and the error matrix of non-commercial forest change information was made to analyse the dynamic change in the observation period.

Results

Optimal method for image enhancement

This research showed that different methods had different impact on the fusion images mainly on brightness, correlation index and other aspects. For Spot-5 image data, Pansharp transformation had the best performance and could be the optimal choice for further classification study. For GF-1 image data, GS spectral sharpening had higher potential for the land type classification than the other methods.

Pix-based classification

Support machine method (SVM) had the highest total accuracy and Kappa coefficient which were 85.64%, 82.72% and 87.19%, 0.83, 0.80 and 0.85, respectively. Furthermore, the results indicated that SVM showed better performance on dealing with shadow. Considering all the factors, in this experiment, SVM was the method that performed best and Mahalanobis distance method was the one with lowest performance.

Object-based classification

For each image data, three-level multi-scale segmentation hierarchy (Spot-5:560, 500, 450, RapidEye: 400, 350, 180, GF-1: 650, 560, 480) was built and rules were set on each level. In addition, dichotomy model was introduced to object level from pix level and the FC value was added to the rules to realize the object-based classification. The classification accuracy of Spot-5, RapidEye and GF-1was 87.1%, 92.3% and 92.1%, respectively, which was higher than pix-based classification methods and more suitable for extracting the changes.

Forest dynamic change in the observation period

Both the extraction accuracies were over 87%, missed rates and error rates were less than 20%. The area of non-commercial forest was increasing from 2004 to 2015 which was mainly reflected on increasing forest land area and decreasing other forest land and agriculture land. These changes were closely related to the higher awareness of protection of non-commercial forest in our country and kinds of projects and policy.

Conclusions

The object-oriented classification approach in this study proved to be a promising method for extracting the dynamic change during the observation period, and it can be extended on large spatial area. Higher extraction information accuracy provides more reliable data to bridge with the modelling data. However, there are still some drawbacks in the object-oriented classification approach, such as lack of versatility for different satellite data. Therefore, to find a set of generalized rule system for afterward research is one of the future goals to monitor the forest dynamic change.

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VARIATION OF JUVENILE-MATUREWOOD TRANSITION YEARALONG THE BOLE OF *PINUS NIGRA ARN*. BETWEEN TWO SILVICULTURAL TREATMENTS.

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Introduction

It is known there are important changes in wood properties along the stem in radial (pith to bark) direction and axial direction, even between earlywood (springwood) and latewood (summerwood) and along the length of the same ring. This variation in wood properties is produced by several factors interacting with the tree, like climate (rainfall, temperature, and soil moisture), site (orientation, slope, and soil), silviculture (stand density, crown size and position, fertilization, pruning, age of harvest) and genotype, among others (Baldwin *et al.*, 2000; Larson, 1969; Larson *et al.*, 2001; Rodriguez & Ortega, 2006 and Rowland *et al.*, 2004). Nowadays due to shorter rotation, an old problem has focused more and more attention, the proportion of Juvenile Wood (JW).

Large proportions of JW have deep negative effects on physical-mechanical and technological properties of the material (Burdon *et al.*, 2004; Ivković *et al.*, 2009; Hermoso *et al.*, 2013; Larson, 1969; Zobel & Sprague, 1998) and can result on different drying distortions, resulting on a lower possibility of final use and economic return in the wood industry.

Usually, basic specific gravity and density are used to determine the JW extent, but also, using micro X-ray densitometry. However, there are other techniques like microfibril angle, and less common, tracheid length and wall thickness. In our case, we will be using micro X-ray densitometry to adjust a model to set the juvenile-mature wood Transition Year (TY).

Materials and methods

Data collection was done in Central Spain, from a pure plantation of Black pine with different experimental thinning and pruning trials. In this area, the average annual rainfall is 489 mm, and the average annual temperature is 10.9 ºC. The trial was installed in 1993 when the stand was 26 years old and five inventories have been carried out since then. During that time two thinnings were done, in 1993 and 2006.This experiment consisted of sixteen permanent plots of 0.1 ha (25x40) divided in four treatments with four repetitions. Here it is presented the study of two of the treatments: a control treatment were only dead trees were removed (C), a medium intensity thinning with 5 m pruning in all the trees (MTP).One pine of each plot, was felled down and every three meters a disc, with a thickness of approximately 15 mm, was extracted, including the basal one and two more at 1.3 and 4.3 meters.

From each disc two stripes 2 mm width, cut from the cross section were extracted, avoiding compression wood. Then they were scanned with an X-ray to assess the stripe microdensity. The images were processed using LIGNOVISION™ and TSAP-Win™ software and averaged values for each growth ring as ring width, mean ring density, earlywood width, earlywood density, latewood width and latewood density and texture were obtained. Afterwards, in order to obtain the transition point from juvenile wood to mature wood, two segmented regression models were used in R statistical package, in a similar way to Di Lucca (1987,1989) and Goudie and Di Lucca (2004). The first model was done using the R-package "segmented" and the second one doing a piecewise regression using the least squared error (LSE) instead of the Maximum Likelihood Error (MLE) used in the segmented package.

Results

In the end the most stable property to obtain the transition point was the Latewood density, so all the results presented here will be obtained using it. Figure 1 and 2 show the results of the TYs determined along the bole for one tree studied per figure.

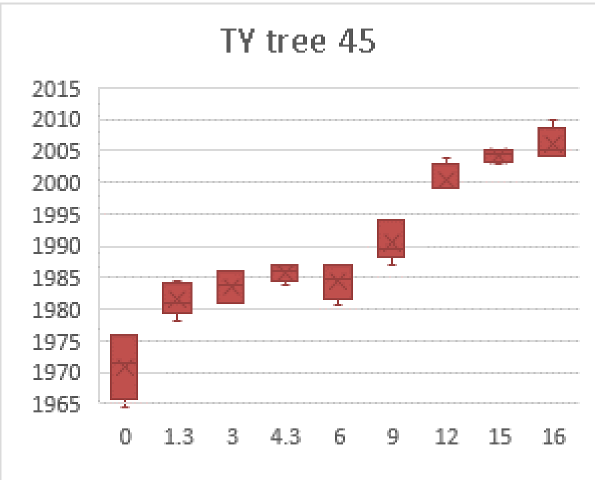

Figure 1: TY obtained for Block II, MTP treatment.

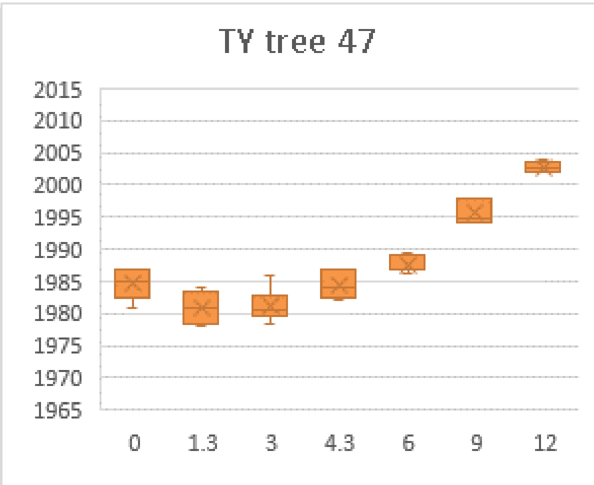

Figure 2: TY obtained for Block Ingo treatment.

When assessing the TY it is important that no compression wood is present because the transition point obtained makes no real sense. To try to avoid this problem, six TY where obtained per height, one from each stripe and the mean of both data per height, for both regression types.

Conclusions

It is important to notice that, the first pruning and clearcutting was done in 1993, so in the heights in which the transition point was obtained before this year, no influence is expected. Comparing the block repetition between Control and MTP treatment it can be observed that has overall lower TY the MTP treatment at 9 meters, so it seems that the pruning with the clearcutting make the tree reach a reduction of the TY.

Also, the percentage of JW volume present at that height is smaller in trees with the pruning and the clearcutting.

Further investigation should be done to see if this is a normal trend or just a local one.

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MODELLING STAND VARIABLES OF PINE FOREST USING SENTINEL-2A DATA AND THE RANDOM FOREST APPROACH

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Introduction

Quantification of stand variables such as volume and biomass is an important issue in forest management. Reliable information is required for accurate stand variables estimation and, traditionally, forest inventory has been carried out by systematically designed field measurements. This approach is expensive and time-consuming; however, the use of auxiliary remotely sensed data linked to the development of statistical frameworks to ensure a rigorous uncertainty assessment (Gregoire *et al.*, 2016) has allowed an accuracy estimation of stand variables at lower cost and over larger areas (Kauranne *et al.*, 2017; Puliti *et al.*, 2018). In this paper, models to estimate the main stand variables of a thinning trial of pine species using data from the moderate image resolution Sentinel-2 satellite have been developed using the random forest approach.

Materials and methods

The study area was located in the North-west of Spain. The dataset corresponds to 41 thinning trial locations installed in pure, even-aged stands of *Pinus pinaster* (22 locations) and *Pinus radiata* (19 locations). At each location, three rectangular plots (1000 m^2 in size) were established and georeferenced by using a differential GPS. A different treatment was applied to each plot: unthinned control, moderate thinning (20% of the basal area removed) and heavy thinning (40% of the basal area removed). The plots were thinned from below in 2010 and were re-measured at different age intervals, although in this study, only the measurement carried on the summer of 2016 was used.

Diameter at breast height (d) of all the trees was measured to the nearest 0.1 cm. Total tree height (h) was measured to the nearest 0.1 m in a randomized sample of 30 trees and in an additional sample of dominant trees (the proportion of the 100 largest diameter trees per hectare, depending on plot size). Total tree height for the remaining trees was estimated using the h-d model developed for these species (Diéguez-Aranda *et al.*, 2009). The number of stems per hectare (N), stand basal area (G), mean height ($\bar{h}$) and stand dominant height (H, defined as the mean height of the 100 thickest trees per hectare) were calculated from tree variables and the tree volume and tree biomass equations developed for these species in Galicia (Diéguez-Aranda *et al.*, 2009) were used to estimate the stand volume (V) and stand aboveground biomass (W).

Cloud-free Sentinel-2A images acquired coinciding with the field inventory of the sample plots were used. The data preparation involved the resampling of the S2 bands to obtain a layer stack of spectral bands at 10 m; the correction of the level-1C data to level-2A (bottom-of-atmosphere) and the calculation of the vegetation indices (VIs). Five band- and VIs-specific metrics (mean, standard deviation, minimum, median and maximum) were extracted from the pixels of each sample plot.

Random Forest was used to relate the stand variables with S-2 bands and VIs by using the randomForest package (Liaw and Wiener, 2002) of the R software (R Core Team, 2017) and setting the number of trees to 1000. Tree species and thinning intensity were initially considered as potential covariates, however, their inclusion in the models implies the need to obtain a classification system of the S-2 images to differentiate between species and thinning intensities, therefore, a classification tree was fitted using the rpart package (Therneau *et al.*, 2017) of the R software (R Core Team, 2017). Two goodness-of fit statistics were used to evaluate the performance of the models: the percentage of the root mean squared error (rRMSE) over the mean value and the square of the correlation coefficient between observed and estimated stand variables (ρ^2).

Results

The classification tree fitted to differentiate between species and thinning intensities is based on features related to Bands 2, 5 and 11 and to the vegetation indices RENDVI and EVI. The overall accuracy was 76.42%, with partial accuracies to classify the species and the treatments of 96.75% and 78.86%, respectively. The predicted classification was considered as a new feature to fit the models. The goodness-of-fit statistics of the random forest models are shown in Table 1.

Table 1. Goodness-of-fit statistics of the random forest models.

Variable	rRMSE(%)	ρ^2
N (stems/ha)	43.4888	0.2330
G (m^2/ha)	24.9248	0.1273
$\bar{h}$ (m)	14.2474	0.5714
H (m)	13.6585	0.6383
V (m^3/ha)	29.5370	0.2546
W (t/ha)	29.1775	0.1642

The observed variability explained by the models ranged from 13% to 64% with the best results for dominant height (H) and mean height ($\bar{h}$). The most important variables to estimate the stand variables were the predicted species and treatment values obtained with the classification tree and features related to the RENDVI and EVI vegetation indices.

Conclusions

The results obtained in this study indicated the models obtained using only features related to Sentinel-2 data are not accuracy enough for stand variables estimation except for stand heights. These poor results contrast with those obtained for other authors using moderate resolution Landsat images (e.g. Zheng *et al.*, 2004; Hall *et al.*, 2006); however, sample plots from a thinning trial of two different pine species have been used in this study, implying a great variability of the stand variables analysed. Therefore, due to the enhanced spatial, spectral and temporal characteristics of Sentinel-2 compared with Landsat, this sensor provides a great opportunity for stand variables estimation and updating and there is a need for further investigation to evaluate the potential of Sentinel-2 data to estimate these variables.

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LOBLOLLY PINE DOMINANT HEIGHT PROJECTION: COMPARING BAYESIAN AND FREQUENTIST NONLINEAR REGRESSION APPROACHES

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Dominant height (DH) is the ultimate indicator of site productivity used to project stand growth. It's definition for even-aged stands in the US southeast, corresponds to the average height from dominant and codominant trees in a stand at a given base age, with the Bailey-Clutter model used as the preferred equation in an operational setting (Borders et al. 2014). Model parameters were estimated using a frequentists approach, with either least squares or maximum likelihood. A key assumption in such methods is the joint Normality between the response variable and the equation parameters. However, projection of normally distributed variables using a non-linear transformation translate in a sub-optimal estimation of future variances with possible biased estimates. A different method to find model parameters, the Bayesian approach, does not impose constraints or assumptions on the posterior distributions as in the frequentist maximum likelihood method. In this case variables are allowed to depart from normality, providing a flexible way to solve for the equation parameters (Davidian and Giltinan, 1995). Bayesian methods have been used in several applications, including diameter distribution estimates (Bullock and Boone, 2007), linear models with heteroskedasticity for estimating tree foliar dry matter (Green and Valentine, 1998), individual tree mortality (Metcalf et al., 2009), stand-level height and volume growth models (Green and Strawderman, 1996), and for a stand level dominant height prediction model (Li et al, 2012). In every case, Bayesian approaches have produced similar outputs (in terms of expected values) to those achieved with maximum likelihood frequentist approaches (Li et al., 2011; Laloy and Vrugt, 2012). The primary benefit of using Bayesian approaches is the ability to generate the full posterior distribution for the estimated parameters (at the cost of more intensive computation). The objective of this study was to compare parameter estimates for the Bailey-Clutter polymorphic algebraic difference equation using either frequentist or Bayesian approaches. Both methodologies were evaluated for differences in parameters estimates, parameter posterior distributions, and model prediction performance. The effects of the assumed prior distributions on the posterior distributions were investigated. We found no practical difference in the posterior distributions of the parameters between the frequentist and Bayesian approaches, however, the prediction intervals using the Bayesian approach are smaller. The use of a Bayesian approach resulted in similar expected values, but a narrower prediction interval at future ages. Our findings are important when evaluating the uncertainty of future investments when projecting over large age differences.

THE ROLE OF SPECIFIC LEAF AREA (SLA) IN GROWTH SIMULATION WITH THE ECOPHYSIOLOGICAL PROCESS MODEL 3-PG

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Introduction

Leaf and branching patterns are criteria to minimize tree construction and maintenance costs and maximize light interception. This physiological process's target is to achieve optimal leaf size and shape according to the environment as an evolutionary process (Parkhurst and Loucks, 1972; Mitchell *et al.*, 1992; King, 1999).

Leaf area relies on the efficiency of the conversion of biomass into assimilating leaves, which ratio is termed specific leaf area (SLA) (King, 1999). SLA is strongly genetically controlled and is under an ontogenetic influence (Mitchell *et al.*, 1992, Karavin, 2013). It is a key factor that constrains forest growth. The accuracy of SLA estimation is a critical step to understand tree dynamics (carbon budget and water flux) and model them through physiological processes (Xiao *et al.*, 2006). In the modelling of 3-PG, SLA is a major driver of tree growth by tracking the radiation absorption and its allocation as biomass. For eucalyptus, the SLA determination is complicated by the marked leaf dimorphism in which young, juvenile leaves are different in shape and size as compared to mature leaves.

Due importance of this subject for 3-PG model calibration, we have studied whether the specific leaf area of Eucalyptus grandis x urophylla varies due to leaf position and plant age.

Materials and methods

The study area are *Eucalyptus grandis x urophylla* stands in Kwambonambi, Zululand aged from 1 to 7 years. For SLA determination in each stand, one tree was sampled by collecting three sub-samples of 25 leaves. The sampling procedure considered the tip, the middle and base of the branch. SLA was calculated as the ratio of leaf area to leaf dry mass ($m^2 \cdot kg^{-1}$). Leaf area was measured with a leaf area meter (LI-3000, Li-Cor).

Results

The SLA values for *Eucalyptus g x u* varied from 8 to 16 $m^2 \cdot kg^{-1}$. They were initially higher (16 $m^2 \cdot kg^{-1}$) at early ages and then decreased rapidly at ages of 2 to 4 years until a lower limit of 6.5 or 7$m^2 \cdot kg^{-1}$at 7 years old (end of rotation) (Figure 1a). On young trees, juvenile leaves had about double the SLA compared to mature leaves (Figure 1a). The SLA values show that SLA is not constant over the tree life and decreases with tree age (Job *et al.*, 2003, Karavin, 2013).The higher SLA of young *Eucalyptus* has been attributed to possible advantages in the seedling phase when rapid development of leaf area with low biomass investment is mechanically beneficial and does provide a competitive advantage due to higher light use efficiency (King, 1999).

The fitted total branch SLA function ($y = -4.367\ln(x) + 15.863$; $R^2=0.805$) was very similar to the one of the middle part of the branch ($y = -4.261\ln(x) + 15.637$; $R^2=0.814$).

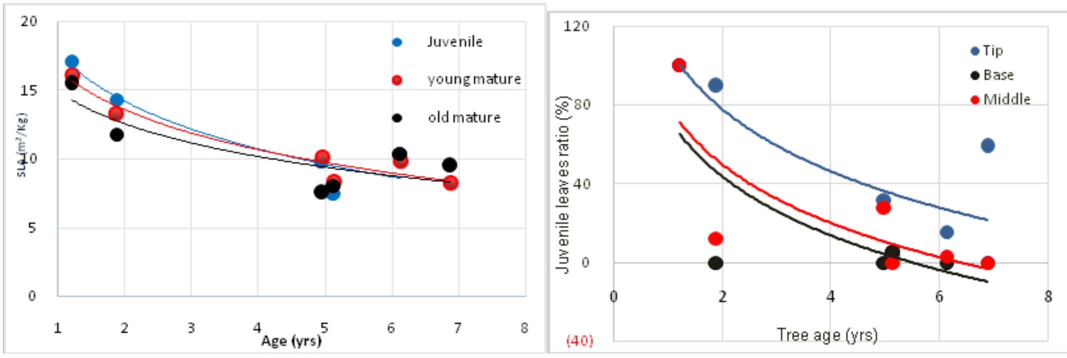

Figure 1: Observed values and trend line of specific leaf area (SLA) (a) and the contribution of branch parts to total SLA according to the tree age in Eucalyptus grandis x urophylla branches sections at ages of 1 to 7 years (b).

Additionally, young parts of the branch had more juvenile leaves but with higher tree age the proportions of juvenile leaves were strongly reduced. The difference in the juvenile leaf proportion explained the SLA change to a large degree (Figure 1b). Calvo-Alvarado *et al.* (2008) suggest that the growth in height results in trade-offs between morphological and anatomical adaptations that favour efficient water flow through variation in the amount of leaf area.

Conclusions

Specific leaf area (SLA) is greater in younger trees and on leaves of the tip of the branch.

Middle leaves can represent quite well the SLA behaviour of the total branch. This assumption could simplify further sampling procedures.

A SLA determination standardized protocol (with tree age and leave position) is needed for these traits. This would allow for better consistency in data collection.

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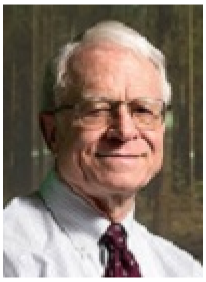
Invited Keynote Speakers

Prof Harold Burkhart (USA)



Prof Harold E. Burkhart is perhaps one of the world's most well-known researchers in forest mensuration and modelling, having published over 250 research papers in journals, research bulletins, book chapters, and proceedings papers. He has also authored two widely adopted books: the undergraduate textbook "Forest Measurements," now in its fifth edition, and the advanced-level book "Modeling Forest Trees and Stands," considered the leading reference for this research specialty. Currently a University Distinguished Professor at Virginia Polytechnic Institute and State University's Department of Forest Resources and Environmental Conservation, Prof Burkhart has been a faculty member since 1969. He has been the recipient of numerous prestigious awards over the years, including the IUFRO Scientific Achievement Award (1981), Virginia's Outstanding Scientist (2013) and the 2014 IUFRO World Congress Host Country Scientific Achievement Award. Prof Burkhart will give a keynote presentation on aspects of the topic "understanding and evaluating uncertainties in models predicting future forest attributes".

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Prof Annikki Mäkelä (Finland)

Prof Mäkelä, from the University of Helsinki is world-renowned for her work in forest modelling research, with over 100 papers published in international peer reviewed journals. She currently leads a forest modelling research group which develops theories and models of tree function, structure, and growth, and applies these to questions relevant to forest management under changing environmental conditions and alternative management objectives. The group is also part of the Centre of Excellence in Atmospheric Science. Her special interests are in understanding how trees capture and allocate resources. Prof Mäkelä will talk on the topic "The cutting edge in process-based and statistical approaches: how we will model future forest attributes in the 3rd millenium".

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Prof John Kershaw (Canada)

Prof John Kershaw, from the University of New Brunswick has specialist expertise in forest mensuration, forest inventory design and analysis, growth and yield modelling and the interplay between these fields. In particular, he has pioneered the application of copulas, a special class of multivariate distributions, in forest inventory, LiDAR analysis, and growth modeling. Well known internationally, he currently works on projects in the USA, Canada, Europe and Asia. He has authored or contributed to over 75 articles in peer reviewed journals and was a lead author on the 5th Edition of Forest Mensuration (Wiley-Blackwell, 2017). Prof Kershaw will talk on the topic "Leveraging big data and high technology in forest models".

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Dr Auro Almeida (Australia)

Dr Almeida, a senior research scientist at CSIRO, based in Hobart, has pioneered the development and application of process-based model in the forestry industry in Brazil, including aspects of wood production, catchment hydrology and climate change. Although Australia-based, Auro has long-term collaboration with research institutes and industries in South America, Southeast Asia, Europe and Oceania. His current research in forest systems and sensing network, is connecting and modelling growth and water forecasting at multiple scales, making models more accessible and easier to use and influencing decision-making processes. He has contributed to over 50 peer-reviewed scientific articles. Dr Almeida will talk on the topic "Model application, integration and accessibility for forest management and planning".

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Prof Dave Auty (USA)

Prof Auty, currently Assistant Professor of Wood Science and Utilization at Northern Arizona University (USA), has a research program focusing on the measurement and modeling of wood and fibre properties, with a particular interest in how variation in wood properties can be incorporated into growth and yield models. This approach allows for predictions of the effects of silvicultural practices on both the volume and distribution of wood properties in the present and the future wood supply. Prof Auty, who collaborates internationally on research in his field, has published nearly 30 peer-reviewed articles in the scientific literature. He will give an address on the topic "The nexus between models of tree growth, wood formation and product properties".

General Information

VENUES AND EVENTS

All conference presentations, including the poster session on Thursday 27th, will be in the main hall at STIAS. The conference dinner on Wednesday 26th will be at the Lanzerac hotel (see maps to follow). All tea breaks and lunches will be served at STIAS. For the poster session on Thursday afternoon, drinks and snacks will be available at no cost for those attending or presenting.

PRESENTATIONS

Oral presentations will be 20 minutes in duration, with 5 minutes for questions given at the end of each talk. Session chairs will keep **strictly to this time limit**. A "roving" microphone will be available for audience members to ask questions. Keynote presentations will be 40 - 45 minutes, with 5 - 10 minutes for questions. Presenters must please ensure that their presentation, in Microsoft Powerpoint (*.ppt or *.pptx) or Adobe Acrobat (*.pdf) format is provided to the team at the front desk no later than one full session prior to their talk/s. Please don't attempt to load your presentation at the beginning of the session in which you are speaking.

Posters must be pinned to boards at the back of the main venue during Tuesday 25th September. Delegates can view posters at any time during the meeting, but a formal poster session will take place on the afternoon of Thursday 27th. Poster presenters must be sure to be present at their posters during this time. Poster presenters will also be given the opportunity to give a (max) five minute "lightning talk" during a session on Wednesday 26th or Thursday 27th (check the schedule) just prior to lunch on both days. These talks will not include projected slides; the presenter should merely draw attention to his/her poster, providing a synopsis of the work. This presentation is not compulsory, and poster presenters need not give a lightning talk if they prefer.

INFORMATION FOR VISITORS

Visitors are recommended to visit https://www.stellenbosch.travel/general-information for a host of information about Stellenbosch, including currency exchange and banking, tipping at restaurants, general safety etc.

Safety in Stellenbosch

Most people who visit Stellenbosch thoroughly enjoy their stay and experience no crime at all. However, rates of crime are higher in South Africa than in many other countries, and vigilance is recommended. If you have a rental car, keep it locked while driving. It is a good practice to store your valuables in a hotel safe or your place of abode. As a general rule, we suggest you don't walk alone after dark in most parts of town, and even in groups, ask advice from local people about areas that are less safe. Around the older, more tourist oriented parts of Stellenbosch, the conference venue and on the University campus, regular patrols are kept, however, and visitors to can feel free to walk to venues and enjoy the beautiful surroundings! It is also generally safe to walk trails on the mountain, but it is advisable to do so in groups of three or more, particularly when the trails are quiet. If you're not sure, ask any one of the Organising Committee.

Some emergency numbers

Should the need arise, the following numbers will be useful in an emergency:

Police Emergency: 10111

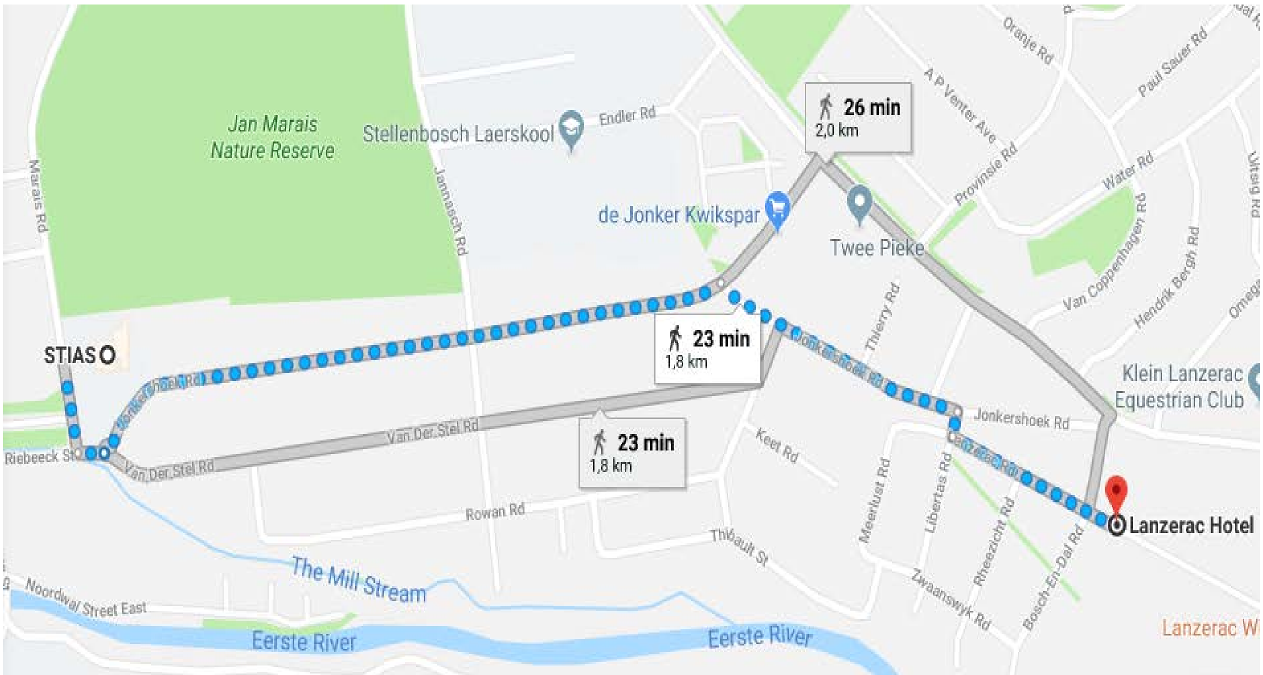
Ambulance: 084 124 (ER24) / 082 911 (Netcare)

Medi-Clinic 24-hour emergency unit: 021 886 9999

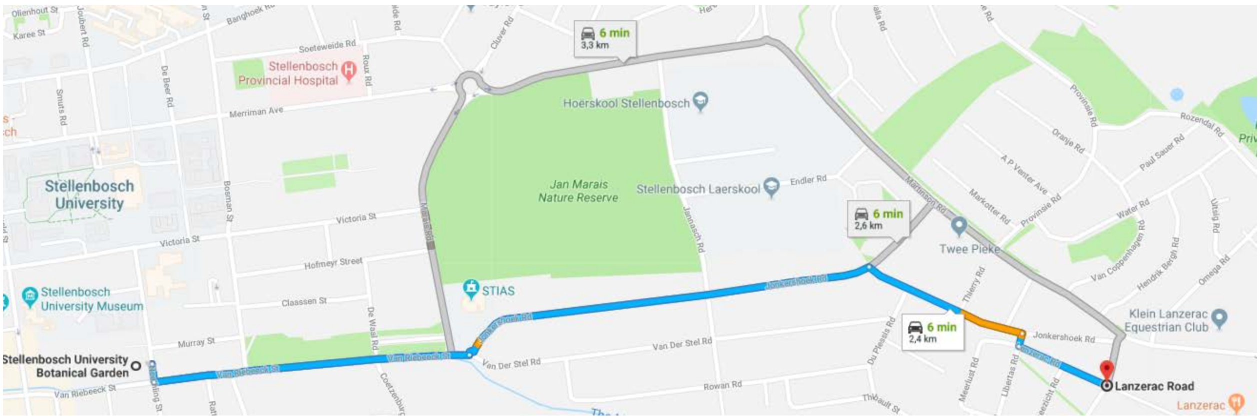
CSCD (University Centre for Student Counselling and Development) 24-Hour Service: 082 557 0880

MAP SHOWING DIRECTIONS FROM STIAS TO LANZERAC

On Wednesday 26th, the conference dinner (for all delegates who registered for it) will be held at the Lanzerac estate. Lanzerac is a very pleasant 20 – 25 minute walk from the conference venue at STIAS. A transport service will be offered, however, starting from 17:45 and running until 18:30. Delegates who would like transport to the dinner should wait at the corner of Neethling and Murray Street (opposite the University Botanical Garden) until the vehicle returns (it will continually loop back to that start point, via STIAS, from Lanzerac between 17:45 and 18:30). After the function, beginning at about 21:00 and ending at 22:30, lifts will again be offered from Lanzerac to the University Botanical Garden in Neethling street.



MAP 1: The walk from STIAS to Lanzerac with estimated walking time. Map used and estimates produced by AfriGIS, Pty. Ltd., Google.



MAP 2: The route of lifts to or from the Lanzerac Hotel and the University Botanical Garden with estimated driving time. Map used and estimates produced by AfriGIS, Pty. Ltd., Google.

CONFERENCE PROGRAM

The schedule of presentations can also be found online on the conference website: visit http://conferences.sun.ac.za/ff2018/NFFF2018.

Day	Session	Chair	Time	Item
Monday			7:30 AM	Tour of Cape Town (Optional)
			4:30 PM	Opening welcome function and early registration (Optional)
Tuesday			8:00 AM	Registration
	Welcome	Drew	8:30 AM	General welcome by Dr D. M. Drew (NFFF chairperson)
			8:40 AM	Welcome from Prof E. Cloete (Vice Rector: Research and Innovation)
			9:00 AM	Welcome from Prof D. Brink (Dean: Faculty of Agrisciences)
	Risk & Uncertainty		**9:20 AM**	**Keynote address: Prof H. Burkhart**
			10:10 AM	Morning tea
		Vanclay	10:35 AM	Lara Climaco Melo, ESTIMATING MODEL- AND SAMPLING-RELATED UNCERTAINTY IN LARGE-AREA GROWTH PREDICTIONS
			11:00 AM	Jean-Romain Roussel, Martin Béland, John Caspersen, Alexis Achim, REMOVING BIAS FROM LIDAR-BASED ESTIMATES FOREST CANOPY METRICS: ACCOUNTING FOR THE EFFECTS OF PULSE DENSITY, FOOTPRINT SIZE AND BEAM INCIDENCE ANGLE
			11:25 AM	Xianglin Tian, EXTENDING THE RANGE OF APPLICABILITY OF THE HYBRID ECOSYSTEM MODEL PRELES FOR VARYING FOREST TYPES AND CLIMATE
			11:50 AM	Hans-Peter Kahle, Chaofang Yue, REVISITING SPACE-FOR-TIME SUBSTITUTION TO PREDICT FOREST PRODUCTION UNDER CLIMATE CHANGE
			12:15 PM	Lunch (at STIAS)
		Tomé	1:30 PM	Cristian Rodrigo Montes, A DYNAMIC STATE-SPACE SPECIFIC GRAVITY MODEL FOR LOBLOLLY PINE USING DATA ASSIMILATION TO IMPROVE WOOD PROPERTY ESTIMATES WITH EXPLICIT UNCERTAINTY
			1:55 PM	Jari Vauhkonen, WHAT DATA ACCURACY SUFFICES FOR STAND MANAGEMENT DECISIONS? A SIMULATION STUDY CONSIDERING DIFFERENT SITES AND INTEREST RATES FOR SCOTS PINE
			2:20 PM	Francesco Minunno, CONSTRAINING PRODUCTIVITY AND CARBON CYCLE PREDICTIONS OF FINNISH FORESTS. DATA ASSIMILATION OF COUNTRY WIDE PERMANENT GROWTH EXPERIMENTS AND NATIONAL FOREST INVENTORY

Day	Session	Chair	Time	Item
Tuesday	Risk and Uncertainty	Tomé	2:45 PM	Morries Chauke, STAND HEIGHT GROWTH MODEL CONDITIONED TO CHANGES IN RAINFALL FOR EUCALYPTUS PULPWOOD IN MONDI SOUTH AFRICA.
			3:10 PM	Cristian Rodrigo Montes, ASSIMILATING DOMINANT HEIGHT MODELS IN SPACE AND TIME TO REDUCE MEASUREMENT COST WHILE REDUCING OVERALL PROJECTION UNCERTAINTY
			3:35 PM	Afternoon tea
			4:00 PM	Gerard Eckard Lindner, David Drew, UNCERTAINTY IN DOMINANT HEIGHT AND SITE INDEX ESTIMATES IN A EUCALYPTUS GRANDIS PLANTATION CASE STUDY
			4:25 PM	Tessie Tong, Mark Frith, MODELING CLIMATE EFFECT ON CARBON SEQUESTRATION USING TREE RING MASS SERIES
			4:50 PM	Gunnar Petter, Nica Huber, Harald Bugmann, QUANTIFICATION AND REDUCTION OF UNCERTAINTY IN PROCESS-BASED FOREST MODELS
Wednesday			8:00 AM	Registration
			8:30 AM	**Keynote address: Prof A. Mäkelä**
	Cutting Edge	Du Toit	9:20 AM	Jerry Vanclay, ASSESSING COMPETITION IN MULTI-SPECIES STANDS
			9:45 AM	Margarida Tome, HYBRIDIZING THE 3PG AND GLOB-TREE MODELS TO EXPAND THE 3PG OUTPUT WITH INDIVIDUAL TREE INFORMATION
			10:10 AM	Morning tea
			10:35 AM	Carlos Gonzalez-Benecke, Horacio Bown, M. Paulina Fernández, LEAF AREA INDEX THRESHOLD FOR OBTAINING AN EXPECTED WATER YIELD FROM PLANTATIONS: A NEW SILVICULTURAL DECISION VARIABLE?
			11:00 AM	Francois Stroh, Martin Pfennigbauer, Frederic Petrini-Monteferi, HIGH DENSITY WAVEFORM LIDAR – ACQUISITION AND PROCESSING METHODS FOR FOREST STAND PARAMETERS DERIVATION
			11:25 AM	Emmanuel Duchateau, Robert Schneider, MODELING THE SPATIAL STRUCTURE OF WHITE SPRUCE PLANTATIONS
	Lightning Talks		11:50 AM	Stephen M Kinane, Cristian R Montes, A MODEL TO ESTIMATE LEAF AREA INDEX IN LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST UNITED STATES USING GROUND BASED MEASUREMENTS AND SATELLITE DATA
			11:55 AM	Xianglin Tian, PREDICTING INDIVIDUAL-TREE GROWTH USING STAND-LEVEL SIMULATION, DIAMETER DISTRIBUTION AND BAYESIAN CALIBRATION

Day	Session	Chair	Time	Item
Wednesday	Lightning Talks	Du Toit	12:00 PM	David Drew, Gerard Lindner, Jerry Vanclay, Michael Battaglia, MODELLING FOREST ATTRIBUTES ACROSS SCALES USING A HIERARCHICAL APPROACH: ACHIEVING GAINS IN INSIGHT WITHOUT GETTING LOST IN THE COMPLEXITY
			12:05 PM	Takele Kassahun Takele Maru, MODELING ABOVE-GROUND STEM VOLUME AND TREE BIOMASS FOR SEARSIA LANCEA (L.F.) F.A.BARKLEY IN CENTRAL BUSHVELD, SOUTH AFRICA
			12:10 PM	Paula Ferrere, Federico Letourneau, Maria Paulina Fernandez, Rosa Teresa Boca, CHANGES OF AERIAL BIOMASS ALLOCATION IN PINUS RADIATA, MEDIATED BY COMPENSATORY MECHANISMS AFTER SILVICULTURAL TREATMENTS
			12:15 PM	Philip Van Niekerk, David Drew, Ben Du Toit, Steven Dovey, ALLOMETRIC MODELS FOR ABOVEGROUND BIOMASS OF EUCALYPTUS GRANDIS X NITENS
			12:20 PM	Lunch (at STIAS)
	Cutting Edge	Almeida	**1:30 PM**	**Keynote address: Prof J. Kershaw**
			2:20 PM	Piotr Tompalski, USING AIRBORNE LASER SCANNING AND DIGITAL AERIAL PHOTOGRAMMETRY TO ENHANCE FOREST FOREST GROWTH AND YIELD PREDICTIONS
			2:45 PM	Christopher Mulverhill, Nicholas C Coops, Piotr Tompalski, Joanne C White, Peter L Marshall, USING 3-DIMENSIONAL POINT CLOUDS TO IMPROVE CHARACTERIZATIONS OF TREE STEMS ACROSS SCALES IN BOREAL MIXEDWOOD FOREST STANDS
			3:10 PM	Ting-Ru Yang, John Kershaw, APPROACHES TO ESTIMATING DIAMETER DISTRIBUTIONS FROM TERRESTRIAL AND AIRBORNE LIDAR VIA COPULAS
			3:35 PM	Afternoon tea
	Application	Kotze	4:00 PM	Steven Bryan Dovey, MODEL DEVELOPMENT AND ADOPTION IN SA FORESTRY: CHALLENGES AND SUCCESSES
			4:25 PM	Stephan Pietsch, Dennis Choruma, Oghenekaro Odume, MODELLING THE IMPACTS OF WATTLE (ACACIA MEARNSII) PLANTATIONS ON ECOSYSTEM SERVICES IN SOUTH AFRICA
			4:50 PM	Christian Salas-Eljatib, Aaron Weiskittel, C Matus, MODELLING TREE-LEVEL MORTALITY OF NOTHOGAFUS FORESTS IN SOUTHERN-CHILE: A MIXED-EFFECTS LEVEL APPROACH
			6:30 PM	**Conference gala dinner (Lanzerac)**
Thursday		Wessels	**8:30 AM**	**Keynote address: Dr A. Almeida**

Day	Session	Chair	Time	Item
Thursday	Application	Wessels	9:20 AM	Susana Miguel Barreiro, João Rua, Margarida Tome, BRINGING FOREST SIMULATIONS TO LIFE: USING A MANAGEMENT DRIVEN SIMULATOR TO IMPROVE FOREST MANAGEMENT IN PORTUGAL
			9:45 AM	Ilaria Germishuizen, MAPPING RISK AT DIFFERENT SPATIAL AND TEMPORAL SCALES FOR SHORT- AND LONG-TERM RISK EVALUATION: THE CASE OF THE EUCALYPT GALL WASP LEPTOCYBE INVASA
			10:10 AM	Morning tea
			10:35 AM	Heyns Kotze, FORECASTING WITH EMPIRICAL STAND-LEVEL GROWTH AND YIELD MODELS AND DROUGHT MODIFIERS FOR SHORT ROTATION EUCALYPTUS PULPWOOD IN MONDI, SOUTH AFRICA
			11:00 AM	GP Scheepers, Ben Du Toit, MODELLING SOIL NITROGEN AND WATER AVAILABILITY TO GAUGE THE RESPONSIVENESS OF SEMI-MATURE PINE TO FERTILISATION IN THE CAPE FOREST REGION, SOUTH AFRICA
			11:25 AM	César Pérez-Cruzado, Juan Alberto Molina-Valero, Ulises Diéguez-Aranda, Juan Gabriel Álvarez-González, Fernando Castedo-Dorado, SITE FORM AS INDICATOR OF SITE PRODUCTIVITY FOR EVEN-AGED STANDS: A CASE STUDY FOR PINUS RADIATA D. DON STANDS IN NORTH-WESTERN SPAIN
	Lightning Talks		11:50 AM	Che Liu, REFINING THE PARAMETERIZATION AND STRUCTURE OF A CLIMATE-GROWTH MODEL OF BOREAL FOREST
			11:55 AM	Man Hu, EXTRACTION OF NON/COMMERCIAL FOREST PLOTS DYNAMIC CHANGE BASED ON OBJECT-ORIENTED CLASSIFICATION IN YANQING AREA
			12:00 PM	Antonio Ruano Sastre, VARIATION OF JUVENILE-MATURE WOOD TRANSITION YEAR ALONG THE BOLE OF PINUS NIGRA ARN. SPECIES BETWEEN TWO SILVICULTURAL TREATMENTS.
			12:05 PM	Stéfano Arellano-Pérez, Miguel Ángel González-Rodriguez, Fernando Castedo-Dorado, Carlos Antonio López-Sánchez, César Pérez-Cruzado, Juan Gabriel Álvarez-González, Ana Daría Ruiz-González, MODELLING STAND VARIABLES OF PINE FOREST USING SENTINEL-2A DATA AND THE RANDOM FOREST APPROACH
			12:10 PM	Derrick Gallagher, Cristain R Montes, LOBLOLLY PINE DOMINANT HEIGHT PROJECTION: COMPARING BAYESIAN AND FREQUENTIST NONLINEAR REGRESSION APPROACHES
			12:15 PM	Cláudio João Cuaranhua, THE ROLE OF SPECIFIC LEAF AREA (SLA) IN GROWTH SIMULATION WITH THE ECOPHYSIOLOGICAL PROCESS MODEL 3-PG

Day	Session	Chair	Time	Item
			12:20 PM	Lunch (at STIAS)
	Wood Properties	Moore	1:30 PM	M. Paulina Fernández, Dominik Florian Stangler, Hans-Peter Kahle, María Menéndez-Miguélez, DRIVING FACTORS OF WOOD FORMATION IN PINUS RADIATA.
			1:55 PM	Justin Erasmus, Brand Wessels, David Drew, THE LINK BETWEEN WOOD PROPERTY VARIATION AND LUMBER STIFFNESS: THE EFFECT OF INITIAL SPACING
			2:20 PM	Yann Cochet, QUANTIFYING THE IMPACTS OF ELEVATED CO2 AND NITROGEN FERTILIZATION ON XYLEM ANATOMY IN LOBLOLLY PINE
			2:45 PM	Sven-Olof Lundqvist, Stefan Seifert, Thomas Grahn, Lars Olsson, Rosario Gil, Bo Karlsson, Thomas Seifert, MODELS OF AGE AND WEATHER EFFECTS ON NUMBERS, WIDTHS AND COARSENESS AND GROWTH OF YOUNG NORWAY SPRUCE
			3:10 PM	Thimagren Naidoo, Arnulf Kanzler, TOWARDS MAPPING WOOD PROPERTY VARIATION WITHIN A EUCALYPT PLANTATION TO BETTER MANAGE PULP FIBRE SUPPLY
	General Poster		3:35 PM	General poster session (with refreshments)
Friday	Wood Properties	Fernandez	**8:30 AM**	**Keynote address: Prof D. Auty**
			9:20 AM	Damon Vaughan, David Auty, EFFECT OF STAND BASAL AREA ON PONDEROSA PINE WOOD QUALITY: FINDINGS FROM A REPLICATED DENSITY EXPERIMENT IN ARIZONA, USA
			9:45 AM	Damien Sellier, THE LIVING STEM: AN INTEGRATED PHYSIOLOGICAL MODEL OF TREE STEM FORMATION FOR PINUS RADIATA
			10:10 AM	John Moore, Dave Cown, David Pont, Yue Lin, Tian Tsong, LINKING KNOWLEDGE ABOUT GROWTH AND WOOD PROPERTIES IN RADIATA PINE - PAST, PRESENT AND FUTURE
			10:35 AM	**Meeting close**
			11:00 AM	Tea and refreshments