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Predicting lumber grade and by-product yields for Scots pine trees

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ABSTRACT

The purpose of this study was to develop models for estimating yields of lumber grades and by-products of individual Scots pine (*Pinus sylvestris* L.) trees using stem and crown dimensions as explanatory variables. Two separate data sets were used: (1) one simulated by the process-based growth model, PipeQual, which provides information about stem form and branch properties. The model was used to predict the 3D structure of Scots pine stems from thinning regimes of varying intensity and rotation periods and (2) an empirical data set with detailed 3D measurements of stem structure. The stems were sawn using the WoodCim sawing simulator and the yields and grades of the individual sawn pieces, as well as by-products, were recorded. The sawn timber was classified on A, B, C and D-grades for side and centre boards separately (Nordic Timber grading). By-products were pulpwood, sawmill chips, sawdust and bark.

The response variables were formulated as proportions of the total volume of each stem. Multinomial logistic regression models using pulp wood proportion as a reference category were developed based on both data sets separately, and each model was tested on the other data set not used in model building. We found that the proportions of A and B grade lumber and pulp wood were inaccurately predicted. By combining data sets we formulated more accurate models. In combined data set's models, the best combination of explanatory variables was diameter of the stem at the breast height, its logarithmic transformation, the height of the living crown (distance from ground to lowest living branch) and the height of the lowest dead branch (branch diameter $\geq$1.5 cm).

The developed approach integrates implications of forest management for the quality of round wood and sawn wood conversion chain. The models can be used to optimize stand management with respect to the value of potential sawmill products.

1. Introduction

Scots pine (*Pinus sylvestris* L.) is a major raw material for the Finnish mechanical wood industry. The area of Scots pine forests has increased during the last few decades because of intensive planting in the 1970s and 1980s. The area of Scots pine forests has increased during the last few decades because of intensive planting in the 1970s and 1980s, also covering relatively fertile soils not typical of naturally regenerated Scots pine. Currently, two-thirds of the forested area in Finland is dominated by pine. During the recent decades, the thinning intensity in Scots pine stands has increased mainly due to the mechanization of harvesting operations, resulting in more sparse stands (Mäkinen and Isomäki, 2004a,b; Mäkinen et al., 2006). Therefore, there has been much public debate regarding whether or not the quality of pine timber has deteriorated.

The number, type and size of branches are important determinants of Scots pine log grades (e.g. Heiskanen, 1965; Uusvaara, 1985; Uusitalo, 1997). Both empirical (e.g. Colin and Houllier, 1992; Roeh and Maguire, 1997; Mäkinen et al., 2003) and process-based models (e.g. Mäkelä and Mäkinen, 2003; Ikonen et al., 2003) have been developed to compare the effects of different management regimes on branch properties along the stem. The branch models combined with growth models enable predictions of 3D structure of stems and logs. Processing of these 3D stem models can then be simulated by wood conversion simulators, e.g. sawing simulation systems (e.g. Todoroki, 1990; Pinto et al., 2006).

Prediction of wood quality without detailed 3D models and conversion simulations can, however, provide adequate information for several purposes. Less detailed models are adequate, for example, to assess the potential product recovery from different stands, to compare wood quality under different silvicultural management regimes, and to select the appropriate raw material for each end use. When combined within the framework of a stand

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growth simulation, models predicting the end product distribution of the stand permit us to take account not only the yield but also timber quality, and further the value of end-products, at the time of harvest.

Models have been developed to predict lumber grade yields of individual trees based on linear regression analysis with continuous dependent variables (Stayton et al., 1971; Yaussy, 1986, 1989; Howard and Gasson, 1989). Later, Prestemon (1998), Lynch and Clutter (1999), Gobakken (2000) and Prestemon and Buongiorno (2000) used discrete multinomial logit and tobit models to predict the probability that a stem or log belongs to a certain quality class. These models assumed that the whole stem or log belongs to the same quality class. Thus, the models predict how stems and logs are, on average, distributed among sawn wood grades. These models can be used for comparing different silvicultural option or valuing stands, but not for predicting quality grade distributions. Recently, Zhang and Tong (2005) applied both an artificial neural network (ANN) approach and traditional regression models to or estimate the product recovery distribution of black spruce (*Picea mariana* (Mill.)) using stem height, diameter and taper as independent variables.

Uusitalo (1997) developed multinomial logistic models for lumber grade distribution of Scots pine logs in final felling. Models of battens and outer boards were separately developed for butt, second and third log. Dependent variables were defined as polytomous responses, i.e. separate dependent variables were estimated for every possible number of sawn timber pieces in all grade classes. Models for outer boards were linear regression models. The results showed that timber grade distribution of logs was mainly related to stem diameter, height of the lowest dead branch and tree height. The study was based on temporary sample plots in 10 stands in south-western Finland, where information about prior management was unavailable.

The aim of this study was to develop a set of models to predict the yields of different lumber grades and by-products of individual Scots pine stems, using as independent variables simple stand and stem properties that are typically available from forest inventories or forest management plans. In other words, our goal was to find a comprehensive model that could replace extensive calculations needed when modelling internal quality of stems and sawing process. We also tested if adding variables describing the past silvicultural regime as independent variables would improve the model performance, or whether stem properties at felling were sufficient to predict reliably the product distribution. We used both a simulated and a measured data set for modelling and model testing. Firstly, a process-based growth model, PipeQual (Mäkelä, 1997; Mäkelä and Mäkinen, 2003) was used for predicting the effects of greatly varying stand management regimes on tree growth and branchiness. The simulated data set was used to describe the effects of widely varying silvicultural treatments on tree growth and wood properties. The second data set, derived from the analyses of real stems, was selected from the Stem Data Bank collected by the Technical Research Centre of Finland (VTT). Both the virtual stems predicted by the PipeQual simulator and the real stems from the Stem Data Bank were used as an input to the integrated wood conversion simulation system, WoodCim (Pinto et al., 2006) to enable the virtual sawing of individual logs and prediction of grade distribution of sawn timber and by-product yields.

2. Material and methods

2.1. Virtual stems

We simulated stand development according to silvicultural regimes of varying intensity by the PipeQual simulator (Mäkelä, 1997, 2002; Mäkelä and Mäkinen, 2003). PipeQual combines stem and branch properties in response to carbon acquisition and allocation by means of a modular structure that contains interconnected modules of stand, tree, whorl, and branch dynamics at a time resolution of 1 year. The model predicts dynamically the growth of individual trees at different dominance positions. The stand level consist of 10 size classes of trees, each size class is described by a mean tree. In the tree module, annual growth is calculated from crown photosynthesis (affected by shading by the neighbouring trees) and maintenance respiration. The annual growth is allocated to foliage, fine roots and woody structures (stem, branches, and coarse roots). The tree module is connected to a whorl module, which contains equations that distribute the vertical structure of stem and branches. The branch module calculates the annual dynamics of individual branches and their properties in each whorl (Mäkinen and Mäkelä, 2003). As a result, we are able to predict the vertical profile of stem and crown, including the heartwood and sapwood zones, as well as characteristic of the individual branches (location, size, status: living/dead and insertion angle) and internal knots in terms of size and angle of knots, zones of tight and loose knots and a knot-free zone at the each whorl of the tree. The process of generating 3D stems using PipeQual is described in detail by Mäkelä and Mäkinen (2003).

PipeQual requires initial values for stem height, stem diameter at breast height (D_{bh}), crown length, and age, as well as the initial number of trees per hectare in each size class. In this study, the initial size classes were separately defined for each planting density in terms of initial seedling height at the age of 8 years, with even class intervals for 10 size classes of trees (Fig. 1). In the simulations, site fertility class was recognized as a *Myrtillus* forest site type (H_{100} = 28 m) (Cajander, 1949) corresponding to sites of medium productivity in southern Finland.

Different silvicultural regimes were designed to produce variation in stand development and growth rate of trees. The regimes were divided into four main groups based on management intensity, named as open-grown, high, normal and low intensity (Table 1). Four planting densities (2000, 3000, 5000, and 10,000 stems ha^{-1}) were simulated in all the regimes, excluding the low intensity where the sparsest planting density was omitted. In sapling stands at dominant height of 6.6–6.8 m, a tending treatment was carried out by reducing the number of remaining stems to 400, 1200, 1900, or 3000 ha^{-1} in reference to open-grown, high, normal, and low intensity treatments (Table 1). In the normal and low intensity treatments, the first commercial thinning began at dominant height of 14 m by reducing the number of remaining stems to 400, 600, or 1200 ha^{-1} (Table 1). In the open-grown and high intensity treatments, at dominant height of 14 m, the stand density did not exceed the density recommended for normal forestry practices (Tapio, 2006) and, therefore, no first thinning was carried out. The stands were later thinned according to the recommendations for forestry practice, expressed as the stand basal area to be retained after thinning (Tapio, 2006). Second and third thinnings were done when the dominant height of the stand was 19 m and 23 m, respectively. The final felling was carried out when the mean D_{bh} of the stand exceeded 30 cm or stand age was 85 years. If there was less than 4 years between these two criteria of final felling, only the first alternative was simulated. Altogether, different combinations of planting densities, tending and thinning intensities and final felling ages resulted in 48 different treatments. The mean trees of the 10 diameter classes in each regime were used in the modelling explained below in more detail. Because some of the size classes were removed in the early phases of the stand rotation and provided no sawn-timber, the final data set consisted of 415 virtual stems (Table 2).