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Evaluation of forest growth simulators with NFI permanent sample plot data from Finland

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ABSTRACT

Tree-level and stand-level forest growth simulators and their combination were evaluated using data from a large network of permanent sample plots of the National Forest Inventory covering the whole of Southern Finland. The simulators were built up with the SIMO framework. The evaluation was carried out both at the stand-level and separately for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), silver birch (*Betula pendula*) and white birch (*Betula pubescens*) strata within the plots. Effects of different factors, e.g. age, soil type, stand density and geographical location on the results were also analysed.

All the simulators provided relative RMSE of around 10% for stand-level tree diameter and height estimates, while the RMSE%s for basal area and the volume estimates were a little bit higher (22–25% and 24–30%, respectively). When estimating height and volume the least biased simulator was the tree-level simulator, while the diameter and basal area estimations were least biased with the combined simulator.

In general the examined simulators seem to work well in circumstances where natural mortality is low or does not exist, as happens to be the case in intensively managed commercial forests. Instead, in unmanaged, unhealthy or non-homogeneous forests the estimates are less reliable. Usually the models tend to underestimate the natural mortality, but with the combined simulator and the birch strata the mortality was also often highly overestimated. It seems necessary to make both the growth and mortality models more adaptable to varying conditions in the future. Also the models for the deciduous trees require improvement.

1. Introduction

Forest growth simulators are essential tools for examining the effects of different treatment scenarios and in helping to determine optimal management solutions in practical forest planning (Pretzch et al., 2008; Hyytiäinen et al., 2006; Hynynen et al., 2005). Numerous advanced simulation systems have been developed for predicting forest growth in different parts of the world, e.g. the large-scale forestry scenario model MELA, which is used in practical forest planning in Finland (Siitonen et al., 1996), SILVA developed in Germany (Pretzsch et al., 2002), Austrian PrognAus (Ledermann, 2006), Slovakian SIBYLA (Fabrika and Ïurský, 2006), Finnish MONSU for multiple use forest planning (Pukkala, 2001) and Canadian Woodstock simulator (http://www.remsoft.com/products.php?id=1).

In spite of the long development history of forest simulators that started already in the 1960s (e.g. models by Newnham, 1964; Vuokila, 1965), there are still numerous problems related to their utilization. First of all, there are problems related to biased or imprecise input data caused by inaccurate inventory methods. For example in Finland regional-scale inventories for private forestry are mainly organized by the regional Forest Centres and carried out at 10–15-year intervals, while larger-scale inventories are carried out by the Finnish Forest Research Institute in the form of national forest inventories (NFIs), which produce statistical information about nationwide forest resources every fifth year. As traditional field inventories are laborious and rarely done nowadays, updated data are not always available for use in the forest planning process. Also, cost considerations often mean that the number of field measurements is insufficient to describe rare or clustered phenomena (Haara and Korhonen, 2004), possibly leading to inaccurate or erroneous input data (Kangas and Maltamo, 2002; Kangas et al., 2004) and thus bias in the simulated results. Measurement errors caused by the

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measuring technique and difficult field conditions can also affect the results (Ihalainen, 1987), although inventory methods have been diversifying recently due to rapid developments in remote sensing techniques such as laser scanning, satellite images and their combinations (Hyvönen, 2007; Maltamo et al., 2006).

Secondly, all the forest growth models contain some kind of error component. Forest growth can be predicted using, e.g. empirical models, which have been developed by fitting the measured data into a model, or by using mechanistic models, where growth is estimated on the basis of the vital functions of trees, e.g. carbon and nutrient fluxes. Both approaches have their advantages and disadvantages: empirical models are more accurate than mechanistic ones under stable conditions, but they cannot be used under changing environmental conditions (Matala et al., 2006). The strength of mechanistic models lies in the fact that their results remain reliable even under new conditions (Pinjuv et al., 2006). Hybrid models, which combine both of these types, have found to be promising for estimating forest growth in a changing environment (Pretzch et al., 2008; Nuutinen et al., 2006; Valentine and Mäkelä, 2005; Mäkelä et al., 2000).

The level at which the forest growth models operate effect also the reliability of the simulated results. Tree-level models, which predict the growth of an individual tree, have nowadays become more popular than stand-level models, at least in Europe (Mäkinen et al., 2008). The latest empirical tree-level models that have been developed in Finland are those introduced by Hynynen et al. (2002). Even though stand-level models ignore variation inside the stand, they have been utilized successfully with many applications (Vanclay, 1995; Atta-Boateng and Moser, 2000; Garcia, 2001). The disadvantage is that usually they cannot be used properly in uneven-aged or mixed stands, and this is one of the reasons why they have been replaced by tree-level models in many cases (Garcia, 2001; Porté and Bartelink, 2002). Tree-level models, on the other hand, are also capable of estimating growth in heterogeneous stands, although there can still be problems with these models because very complex interactions between trees and the environment cannot be included in any model in sufficient detail (Schmidt et al., 2006).

There are also differences in the reliability of models between different kind of forests, regions and soil types (Hynynen et al., 2002). Insufficiencies are evident especially in models describing regeneration dynamics (Miina et al., 2006) and the development of young stands (Huuskonen and Miina, 2007). Also, growth estimates for peatland stands are often more unreliable than those for mineral soil stands (Hynynen et al., 2002), due to higher variation in water and nutrient balance in drained peatlands (Jutras et al., 2003). In addition, there are differences in the reliability between the models for different tree species.

As the growth simulators consist of models constructed separately for each variable, the interactions between variables during the calculation process are often very complicated and difficult to assess (Fahlvik and Nyström, 2006). Therefore, the reliability of the simulator itself can remain unclear, even though the reliability of the separate models was known. The newest effort in Finland towards an adaptable and flexible simulation system for forest planning is SIMO (SIMO framework web pages), a simulator developed at the University of Helsinki (Tokola et al., 2006; Rasinmäki et al., 2009). As SIMO is an open source program driven by external XML files (eXtensible Markup Language), it enables transparent tracing of the model interactions.

The main aim of the present work is to compare growth estimates produced by three different simulators constructed using the SIMO framework and to evaluate their reliability with a large NFI dataset from Southern Finland for the years 1985 and 1995. Reliability of the models for Scots pine, Norway spruce and birches are examined separately. Effects of site fertility, stand age, stocking density and geographical location on the results are also analysed. The tested simulators include (1) a tree-level simulator, (2) a stand-level simulator and (3) a combined simulator, where the first 5 years are simulated with the tree-level models and the rest with the stand-level models. We hypothesize that the combined simulator would be the most efficient alternative for predicting growth for forest planning purposes, while it combines the advantages of the both model types: accuracy of tree-level models in the short-term estimations and stability of stand-level models in the long run (Shortt and Burkhart, 1996; Mäkinen et al., 2008).

2. Material

2.1. Test data

2.1.1. Finnish National Forest Inventory data

The main material used in this study was based on the permanent sample plots of the Finnish National Forest Inventory (NFI) located in Southern Finland and established by the Finnish Forest Research Institute. The NFI sample plot network was based on systematic sampling of field tracts, where each tract in Southern Finland included four plots located 400 m apart (from north to south), the tracts themselves being 16 km apart (from north to south and from east to west). The plot size varied according to the tree diameter at breast height, being 100 m^2 when the diameter was under 10.5 cm, and otherwise 300 m^2. The locations of the tracts are presented in Fig. 1. More details of the Finnish NFI, which has fairly similar history and principles as, e.g. Swedish NFI (Tokola, 2006), can be found in article by Tomppo (2006).

All the Southern Finland NFI plots (below latitude of around 65°) which had been measured both in 1985 and 1995 were included, with the exception of plots located on the waste or scrub land, plots which consisted of two or more stands either in 1985 or 1995, plots where there had been cutting during the simulation period and some plots with easily detectable coding errors, such as a large number of missing trees according to the data without cutting. Also, all dead trees were excluded. Total of 837 plots fulfilled the above criteria.

The NFI material contained the following tree data: diameters at breast height for all the trees and heights for the sample trees, from which mean and total values per hectare were aggregated for each plot. The reference data for 1995 contained only the trees that already existed in 1985 and were still alive in 1995. The trees were identified as the distance and angle from the sample plot identification point. A calliper was used to measure the diameter at breast height and a Suunto hypsometer to measure tree height. As the material still contains some damaged and diseased trees, it may cause some bias in the simulations.

The average values for the stand variables on the plots are presented in Table 1. Altogether 69% of the plots were on mineral soils, the rest being on peatlands. Scots pine was the main tree species (in terms of basal area) on 51.3% of the plots, Norway spruce on 38.1%, birches on 10.4% of the plots.

2.1.2. Weather data and estimation of growth season lengths

National weather statistics data from the Finnish Meteorological Institute were used to scale the simulated growth of the first and the last simulation year to match the NFI measurement dates. The data contained interpolated grid (10 km × 10 km cell size) of daily mean temperatures for the years 1985 and 1995 for the whole Finland. ArcGIS was used to combine the NFI plot data with the nearest weather statistics.

A scaling procedure was based on the studies of Raulo and Leikola (1974), Salminen and Jalkanen (2007), Partanen (2004), and Hänninen and Kramer (2007), which establish that annual height growth starts when a certain site-specific and species-specific temperature sum is exceeded and that a similar rule seems to be valid for the end of growth. Species-specific proportions of