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PHD THESIS

LONG-TERM FOREST PROGNOSIS MODELS

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Introduction and scopes of the research

Until the mid-1990s, forest growth modelling was a dominant topic in the Hungarian forest sciences. Professor László Király applied the concept of normal forest to beech stands in Hungary and developed a mathematical description of normal forest. His school-creating theses have gained international recognition. Forest growth modelling and carbon cycle modelling has become even more relevant as the complexity of the burden on forests and the growing need for sustainable forest management arose. The contradictory goals of economic efficiency and nature conservation, the competitive uses of the wood yield (e.g., as raw material for wood products, as source of renewable energy, or as carbon storage in the standing volume) can only be balanced with conscious and considered planning and foresight. The set of problems is further exacerbated by the process of climate change, which is creating increasingly unfavourable production conditions for forests in Hungary; and the increasing food prices and many other factors lead to changing land-use patterns.

From the forest inventories (e.g., National Forestry Database; NFD), different statistics and tables can be produced which describe the structure of the forests, the tree species composition and age class structure, the felling age distributions and the regeneration practices, site conditions etc. The aim of the research is to develop based on these data methods and procedures that can be used to create a model of final harvest and regeneration regimes, and of their modifications attributable to climatic and legislative changes. The other related goal of my research was to create a model which is able to forecast under different scenarios the future state and processes of the forest, based on the descriptive data of the NFD. The purpose of the application of the model is to outline the possible and likely future development trajectories of the forest, with special regard to the changes in the forest management approach and the large-scale changes in the growing conditions (driven by the ongoing climate change).

Experimentation with extreme situations is common in the modeling literature. This is very useful for mapping the boundaries of possibilities and the maximum potentials. However, these scenarios are rarely likely and realistic. It is of prime importance to create a realistic approach of the regulatory processes of forest management and to describe the regeneration and harvest conditions according to the known facts (BAU – Business as Usual scenario). In addition, it is important that the results of the model can be validated based on the historical data of the NFD and the correctness of the model procedures and parameters can be checked.

The NFD has received justifiable critique for its wood stock calculation problems and sampling uncertainties. Acknowledging the validity of these criticisms, work must be done to resolve the issues. However, I would like to point out that despite all the above, the NFD also has an outstanding wealth of data in comparison with the forest inventories other countries in Europe and worldwide have. It has long time series and detailed spatial resolution. NFD was not designed for cost-effective provision of data services. The NFD was designed as a complex model of the forests, on the basis of which regulation can be implemented. It's wealth of data makes possible to recognize, understand and forecast the processes described in the DAS model (e.g., realistic harvesting age distributions and regeneration matrices can be derived). This is an exceptional opportunity for Hungarian forest science and practice.

Materials and Methods

I developed the DAS forest model (Distributions Applied on Stands model) which is a forest stand based model suitable for the projection of standing volume, increment, harvest, and carbon sequestration on the stand level as well as regional or country level. The modelling unit of the DAS model is the forest subcompartment. The DAS model uses the data of the National Forestry Database (NFD) including geospatial data. The model is suitable for the further processing of spatially explicit input parameters such as climate change forecasts. The output of the model is also georeferenced and can be processed using GIS software. The model handles the data of approximately 600,000 forest subcompartments. The tree species row is the sub-unit of the model. Data on tree species, origin, age, growing stock, increment etc. of each subcompartment is stored in tree species rows. The model simultaneously processes the data of 1.2 million tree species rows and describes their development in time. The parameters used by the model are based on the actual processes of the reference period. The model uses empiric cutting age distributions and a regeneration matrix derived from historic NFD data.

The DAS model has a bottom-up architecture which means that volume stock data of a stand is produced by summing up volume stock data of the tree species rows assigned to that stand. Regional and country level data is also derived as the sum of the data of the subcompartments belonging to the given geographical unit. The model uses the Microsoft Visual FoxPro programming language and runs in Windows environment. The used input and the produced output files are in dBase, WKT and CSV format.

<u>A forest subcompartment-based modelling approach</u>

The DAS model is a forest-stand based model which is suitable for the projection of standing volume, increment, harvest, and carbon sequestration on the stand level as well as regional or country level. The modelling unit used is the forest stand as this is the base unit of forest management in Hungary and forest subcompartments have rather homogenous characteristics. The "tree species row" is the sub-unit of the model which is assigned to a forest subcompartment. Data on the growing stock of each forest subcompartment is stored in tree species rows. The tree species rows of the same forest stand differ from each other in at least one of the following attributes: tree species, origin, age, or layer. The model simultaneously processes the data of more than one million tree species rows and describes their evolution in time.

<u>Increment modelling with yield tables</u>

The model uses yield functions by Gál (1980, 1988) for the calculation of the tree height as a function of the age of the stand. Yield functions are based on yield tables and are suitable for computerised data processing. The DAS model uses the yield tables which are also used by the Forest Authority and in the NFD. This ensures the coherence and interconnectivity with the NFD, and with projects based on NFD data such as the Hungarian Greenhouse Gas Inventory, and numerous nature conservation, economic, wood industry, and climate change projects. Forest management planning usually takes place every ten years, during forest management planning field measurements are undertaken and data of those measurements is stored in the NFD. However, between two planning events the annual increment is calculated for every tree species row based on yield tables. The DAS model uses the same yield tables as the NFD, but the calculation method of the growing stock is different. In the NFD the current annual increment is added to the growing stock data of the previous year for each tree species row and annual harvest is subtracted from it. In the DAS model the total growing stock is recalculated as a function of the age of the stand for every subsequent year. Thus, it is not necessary to separately calculate the harvested volume for thinning and precommercial harvests as these are included in the stock data predicted by the yield tables. The yield table-based processing of the DAS model also allows for the modelling of the effect of the changing climate parameters on the productivity of the stand as the yield class parameters can be changed accordingly over time.

Total area of final harvest as a driver

In the model the final harvest is defined by the area affected with final harvesting events. Clear cuttings, gradual renewal cuttings, and other harvests which generate the obligation of forest regeneration are regarded as final harvests. According to my previous examinations the total area of final harvest as defined above is quite stable in time and it is not closely related to the yield area that can be derived from the cutting ages specified in the forest management plans. It is also independent from the fluctuating wood market trends. Since 1990 the area under final harvest was around 20-23 thousand hectares and a slight expansion of the area could be observed in the last decade.

According to my research a significant part of the forest stands is not harvested at the cutting age prescribed in the forest management plans. Historic data series show that only approximately the two thirds of the stands reaching their cutting age are actually harvested. From this, I drew the conclusion that the actual harvest regime in the medium term is not primarily determined by the age-class structure of the forest stand, nor by the felling prescriptions of the forest management plans. Cutting age prescriptions can only be regarded as the potential for harvest, but actual harvests are primarily determined by external factors as timber harvesting capacities, nature conservation restrictions, and wood market demand, etc. The DAS model uses a parameter sheet where the area under final harvest can be prescribed and changed according to the prerequisites of each scenario applied.

Cutting age distributions and the probability of final harvest as a function of the age of the stand

The DAS model does not define cutting ages for the subcompartments processed. The final harvests in the model are regulated by cutting age distributions which assign a final harvest probability to each cutting age. In Japanese forest modelling a similar cut-parameter dependent on the age of the subcompartment is used and it is called "Gentanritsu" (or "Gentan") and it determines the forest area that is cut at a time-period. The age-dependent harvesting probability ratio distributions used in the DAS model are derived from historic NFD data. Thus, a subcompartment's final harvest time is not predefined. Subcompartments available for final harvest are selected according to their age, subcompartments with special nature conservation requirements and continuous cover forests are excluded. Subcompartments actually harvested are selected randomly from the pool of subcompartments available for final harvest according to the age-dependent harvesting probability ratio distributions and the total area of final harvest as prescribed in the parameter sheet. The model uses the distributions of the regulatory parameters at the forest level, and projects these distributions onto individual forest stands by random selection.

The advantage of this method is that different cutting age distributions can be applied in different sub-periods of the forecast and management transitions can be modelled. For example, the increase of cutting ages due to nature conservation reasons, or the decrease of cutting ages in private production forests due to changes in related regulations can be taken into account, and the cutting age distributions can be changed accordingly in the different scenarios and in different time periods. The model can also adapt to the changing age-class structure of the forest. If the area of a given age-class accumulates its forecasted yields also increase. Salvage logging can also be modelled by incorporating final harvests at younger age-classes.

The cutting age distributions are usually not closed i.e., not the 100% of the area is harvested in the last age class affected by final harvest. This means that using the above-described approach some subcompartments are never harvested in the model if they reach the maximum of their cutting age and are not selected for harvest. These subcompartments persist in medium-term projections and model the well-known but not precisely defined phenomenon of Forests Not Available for Wood Supply (FNAWS). In long-term projections though additional parametrisation will be required as these stands may not subsist forever, they might collapse, or transform, or be transformed to continuous cover forests.

Transition matrix of forest regenerations

Forest regeneration patterns in the DAS model are driven by a so-called forest regeneration transition matrix. The currently used forest regeneration transition matrix is derived from NFD data of 2006-2015. In the NFD each subcompartment under regeneration is linked to its previous state (i.e., before final harvest). Thus, the NFD stores data on tree species and origin (coppice, high forest) of a stand for two states, i.e., before final harvest and after regeneration. In the period 2006-2015 such data is available for 69% of the regenerated stands.

The application of the forest regeneration matrix in the DAS model makes it possible to change the forest regeneration patterns in time or along different scenarios. Thus, the effects of changing climatic conditions affecting tree species distribution can be taken into account and tree species replacements during regeneration can be modelled.

Pools of the model

The DAS model uses pools for its processing. The pools are groups of sample forest subcompartments from which subcompartments are selected for regeneration and afforestation during the model runs. The driver of the selection is the tree species, the origin, the yield class, and county code for localization purposes. The current version of the model uses three pools: the pool of regeneration, the pool of afforestation and the pool of found forests. Found forests are forests previously unknown by the Forest Authority and identified during the field survey associated with forest management planning. Found forests can be the result of natural expansion of the forest area or that of geodesic remeasurements too.

The afforested stands enter from the pool of afforestations in their state at the time of the completion of the afforestation (with data on tree species composition, yield class, etc. stored at that time) and for previous years data is counted backwards from this state for the estimated year of the initial planting. The pool of afforestation contains 17 thousand subcompartments in total with an area of 78 thousand hectares. The pool of regeneration contains 37 thousand subcompartments, with the total area of 120 thousand hectares.

New scientific results (theses) and conclusions

1.) I summarized and critically interpreted the work of Professor Király László. I realized the synthesizing summary by processing manuscripts and unpublished research reports, since there are few publications of the Professor publicly available in journals or books.

2.) I found that the distribution of the actual cutting ages is much more balanced, and bell shaped than the distribution of cutting age prescriptions defined in the Forest Management Plans. The timber market demands balance out yields, as does the workforce available to carry out forest operations. Thus, forest managers balance the distribution of the cutting ages prescribed in Forest Management Plans.

3.) I found that the total annual area under final harvest is quite stable and there is no strong connection between the size of the potential area available for final harvest defined by harvest prescriptions of the Forest Management Plans and the size of the yield area of actual harvests. According to my research, from all the area available for final cutting within 30 years as reported in the standard statistics of the NFD, approximately the two-third is actually harvested in the relevant period. From this, I drew the conclusion that the real final harvesting regime in the medium term is not primarily determined by the age-class structure of the forest stands, or the regulations of the forest management plans (which gives only the potential), but it is mainly regulated by external factors (such as timber harvesting capacities, wood market demand, etc.).

4.) I measured the actual cutting age distributions of the Hungarian forest management practice (from 1990 to 2021). The regulatory parameters of previous Hungarian forest models were based on estimates or expert judgements on cutting ages, or they worked with normative rules (e.g., cutting ages of tending models). With cutting ages derived from historic NFD data the projection became much more accurate and reasonable.

5.) I created regeneration transition matrices derived from NFD data of the 2006-2015 reference period. The regeneration transition matrices describe tree species replacements typical of Hungarian forests. This way I was able to include the impact of tree species replacements in the projection model.

6.) I created the DAS forest model, which differs from the aggregated age-class models in the feature that it is based on the individual processing of forest subcompartments. The model can be parameterized individually at the forest stand level and the results can be examined both at the stand level and at aggregated levels. The DAS model is more flexible than the aggregated age-class models, therefore it is able to model environmental effects (like climate change) on a small scale, in a spatially explicit way.

7.) I concluded that in the BAU scenario the management of Hungarian forests is sustainable at the country level and in the medium term. This conclusion applies to the BAU scenario assuming that the management conditions, the harvesting and regeneration patterns of the reference period (2005-2015) remain stable, and especially the extent of forest damage does not change radically. According to the results of the modeling in the BAU scenario the increment is not expected to disappear in the projection period. The previously assumed drastic reduction of carbon sequestration and the possibility that Hungarian forests turn into a source of emissions can be disapproved under the BAU conditions.

8.) I found that the forest stand based DAS forest model is suitable for the projection of the standing volume, increment, harvest, and carbon sequestration of forests on regional or country level; and bearing in mind the limitations arising from the stochastic nature of the model, projections are also possible at a relatively low level of aggregation.

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