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The Re-parametrization of the DAS Model Based on 2016-2021 Data of the National Forestry Database: New Results on Cutting Age Distributions

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Abstract – This paper presents the DAS forest model (Distributions Applied on Stands model), a forest stand-based model suitable for projecting standing volume, increment, harvest, and carbon sequestration on the stand, regional, or country levels. The forest subcompartment is the modelling unit of the DAS model, which uses National Forestry Database (NFD) data, including geospatial data. The model is suitable for further processing spatially explicit input parameters such as climate change forecasts. The model output is also georeferenced and can be further processed using GIS software. The model handles the data of approximately 600,000 forest subcompartments. Data on tree species, origin, age, growing stock, increment etc. of each subcompartment are stored in "tree-species rows", which are the sub-units of the model. The DAS model simultaneously processes the data of 1.2 million tree species rows and describes their development in time. It uses parameters based on the actual processes of the reference period. It also uses empiric cutting age distributions and a regeneration matrix derived from historic NFD data. The ForestLab project (TKP2021-NKTA-43) is currently engaged in the re-parametrization of the model based on 2016–2021 data. This study discusses the functions of the harvesting ratio distribution in the modelling process and in determining the subcompartments selected for harvest. The paper presents the latest results regarding the 2016–2021 cutting age distributions and the preparation of the new set of species-specific and yield class-specific average harvesting ratio distributions.

cutting age / harvesting ratio / forest model / climate change / carbon storage

Kivonat – A DAS modell újra paraméterezése az Országos Erdőállomány Adattár 2016-2021 közötti adatainak alapján: a vágáskor eloszlásokra vonatkozó új eredmények. Cikkünkben bemutatjuk a DAS modellt (Distributions Applied on Stands model), mely egy erdőrészlet alapú erdőállomány prognózis modell, amely alkalmas az élőfakészlet, a növedék, a kitermelt elő- és véghasználati fatérfogat és a szénmegkötés előrejelzésére erdőrészlet szinten, valamint regionális és országos szinten is. A modell az Országos Erdőállomány Adattár adatait használja. Alkalmas térben explicit input-paraméterek fogadására (pl. klímaváltozási előrejelzések) és az eredmények térképi megjelenítésre is, így azok térinformatikai szoftverekkel feldolgozhatóak. A modell kb. 600 ezer erdőrészlet és 1,2 millió fafajsor adatait kezeli. A szabályzó paramétersorok a referencia-időszak ténylegesen tapasztalt folyamatain alapulnak: a modellben valós vágáskor-eloszlások és valós felújítási viszonyok működnek, azaz a modell historikus adatokból levezetett véghasználati- és felújítási mátrixokat használ. A modell újra paraméterezése a 2016-2021 időszak historikus adatainak felhasználásával jelenleg zajlik az ErdőLab projekt (TKP2021-NKTA-43) keretében. Cikkünkben ismertetjük a véghasználati hozami terület arányok eloszlásának funkcióját a modellezési folyamatban és a véghasználatra kerülő terület meghatározásában. Emellett bemutatjuk a 2016-2021-es időszak

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vágáskor eloszlásaira vonatkozó legfrissebb vizsgálatunkat, és a modell újra paraméterezéséhez használt új fafaj- és fatermési osztály specifikus véghasználati mátrixok előállítása során elvégzett munkát.

vágáskor / véghasználati hozami terület arány / véghasználati mátrix / erdőállomány prognózis / klímaváltozás /szénmegkötés

1 INTRODUCTION

Forest sustainability and yield were significant problems for forest sciences in the past, particularly for forest taxation (Suzuki 2003). The ‘normal forest’ concept was developed in Germany in the 19th century. Hans Carl von Carlowitz – a silver mine administrator in Freiberg – was the first to recognize the necessity of sustainable forest management. In the early 18th century, Hundeshagen (1848) in Tuebingen developed a concept of an ideal forest with the same area for each age class over a cutting cycle. He called this ideal forest concept the ‘normal forest’. The concept stipulated that the same age class distribution should remain whenever the oldest stand at the last age class is felled (Leslie 1966, Suzuki 2003). An age-vector space was introduced for normal forest modelling, with forest growth and thinnings represented by a transition matrix acting on the age-vector space (Suzuki 2003).

Yield prediction for domestic forest resources was crucial in Japan in the 1960s. The aim of predicting future forest resources led Japanese researchers to rediscover traditional German forest science and implement the normal forest concept in practice (Suzuki 2003). Matrix-algebra mathematics provides evidence that the time-independent distribution of harvesting ratios ensures a steady state forest in the long run. The concept of this stable state is inextricably linked to that of sustainable forest management and was referred to by Suzuki (2003) as the ‘normal forest in the wide sense’, contrasting it with Hundeshagen’s (1848) normal forest with a single cutting age. The ‘normal forest in the wide sense’ term is identical to the normal forest with continuous cutting age distribution as described in Király’s (1995) normal forest-type classification. Suzuki (2003) introduced a harvesting ratio or cut parameter dependent on the age called “Gentanritsu” (or “Gentan”) to determine the forest area felled during a given period. Assuming a time-dependent change for the management objective, Yoshimoto (1996a) introduced a nonstationary Poisson process to capture the harvesting behaviour for Gentan probability estimation. He applied a time-dependent average growth function for stochastic modelling and introduced a time-dependent change in economic factors (Yoshimoto 1996b).

Forest growth modelling dominated the Hungarian forest sciences until the mid-1990s. Professor László Király applied the normal forest concept to beech stands in Hungary and developed a mathematical description of a normal forest (Király et al. 1992, Király – Mészáros 1995). His model was used in forest management planning practice. His research results and theses have gained international recognition, and his work has become fundamental in the Hungarian forestry science.

Forest growth modelling and carbon cycle modelling have become increasingly relevant as the complexity of the burden on forests and the growing need for sustainable forest management rise. Only conscious and careful planning and foresight can balance the contradictory goals of economic efficiency, nature conservation, and the competitive uses of wood yields (e.g. as raw material for wood products, a renewable energy source, or a carbon sink). Climate change exacerbates this set of problems by negatively influencing production conditions for Central European forests and increasing natural disturbance risks.

Simulating photosynthesis or empirical yield curves drive growth in forest carbon cycle models. Photosynthesis-driven process-based models (e.g. Biome-BGC, Running – Gower 1991, CENTURY, Metherall et al. 1993, 3-PG, Landsberg – Waring 1997, TEM, Tian et al. 1999) require input datasets such as leaf-area index (Running – Gower 1991), climate variables, and soil variables (McGuire et al. 2002). Empirical yield data-driven models like EFISCEN (Nabuurs et al. 2000), CO2FIX (Masera et al. 2003), or FORMICA (Böttcher et al. 2008a) require data on merchantable wood volume as a function of stand type and age. These are the same data represented in national forest inventories (NFI) and used by operational foresters in timber supply analysis and forest management planning tools (Kurz et al. 2009, Pilli et al. 2013). Yield-driven models are particularly well-suited to explicitly simulate human activities and natural disturbances on the current and near-future forest carbon stocks and fluxes (Pilli et al. 2017). These models simulate growth and calculate carbon stocks based on past observations, and they are the primary tool to simulate the detailed effects of different forest management options in short-term forest carbon dynamics (Böttcher et al. 2008b, Pilli et al. 2013) at forest stand to country levels (Pilli et al. 2016).

Hungarian researchers experimented with the EFISCEN model in the mid-1990s by contrasting it with the Király model. Researchers preferred the Király model for forest management planning purposes. In the second commitment period of the Kyoto Protocol, Hungary accounted for its carbon removals in the forest management sector against a Forest Management Reference Level developed with the assistance of the Joint Research Centre of the European Commission and in collaboration with two EU modelling groups using the G4M (IIASA 2023) and EFISCEN (UNFCCC 2011) models. The Biome-BGC model was also parametrized for Hungarian circumstances, resulting in the Biome-BGCMuSo model (ELTE 2023). The model performed the biospheric carbon dioxide balance estimation for Hungary in 2009 (Barcza et al. 2009).

The first Hungarian country-specific Carbon Sequestration Model for Forestations (CASMOR) was developed by Somogyi (1997) based on Comprehensive Mitigation Assessment Process COMAP (Sathaye et al. 1995). The CASMOFOR model (Somogyi 2019) is a newly developed version of the previous model based on IPCC methodology and considering domestic forest characteristics. The CASMOFOR model led to a new dynamic growth model for all Hungarian forests called CASMOFOR-NFDB (Somogyi et al. 2019; Somogyi 2020) to fulfil new reporting requirements arising under the Paris Agreement and Regulation (EU) 2018/841 and to develop a country-specific Forest Reference Level (FRL). The developed model is consistent with the Hungarian Greenhouse Gas Inventory (GHGI) and is based on IPCC methodological guideline principles. The main source of activity data used by this modelling approach is the National Forestry Database (NFD) and data from the Hungarian GHGI. NFD data of forest subcompartments as input is used instead of yield tables and silvicultural models to ensure higher consistency with the GHGI (Somogyi et al. 2019, Somogyi 2020).

Within the frame of the Agroclimate 2 project, a new Hungarian forest projection model, the DAS forest model (Distributions Applied on Stands model), was developed in 2015 (Kottek 2017). The DAS model is also based on NFD data, but unlike the CASMOFOR-NFDB model, it uses the same yield tables as the NFD and is georeferenced. Results are linked to forest subcompartments and can be further processed using GIS software. Thus, the DAS model is suitable for projecting standing volume, increment, harvest, and carbon sequestration on the stand, regional, or country levels. This paper introduces the DAS model structure and characteristics focusing on harvesting parametrization and age-dependent harvesting ratio estimation. The second part of the study presents the latest results on cutting age distributions derived from NFD data and the applied changes in the parametrization of the final harvesting probability related to the planned re-run of the model.

2 CHARACTERISTICS OF THE DAS MODEL

2.1 A forest subcompartment-based modelling approach

The DAS model is a forest-stand-based model suitable for projecting standing volume, increment, harvest, and carbon sequestration on the stand, regional, or country levels using forest stands as the modelling units. Also called subcompartments, these units have homogenous characteristics and are the base units of forest management in Hungary. The DAS model uses NFD data, including geospatial data. The model output is also georeferenced, and can be further processed using GIS software. The model handles the data of 600,000 forest subcompartments.

The sub-unit of the model is the “tree species row”, assigned to a tree species in 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 vary 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.

The DAS model has a bottom-up architecture, meaning that stand volume stock data is produced by summing up volume stock data of the tree species rows contained in 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 Microsoft Visual FoxPro programming language and runs in a Windows environment. The used input and the produced output files are in dBase, WKT and CSV format.

2.2 Increment modelling with yield tables

The model uses the yield functions by Gál (1980, 1988) to calculate the average stand height as a function of stand age. Yield functions are based on yield tables and are more suitable for computerized data processing. After the average height at the given age is calculated, the growing stock is estimated using the yield tables applied in the NFD. These yield tables are the digitalized versions of the graphic yield tables prepared by László Király and his colleagues in 1971-1972 and are used numerically in the NFD. The Hungarian dendrometry literature refers to these as first-generation nomograms. Using the same yield tables for growing stock estimation applied in the NFD ensures coherence and interconnectivity with the NFD and 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 which measurements are taken. The measurement data are stored in the NFD. However, between two planning events, the annual increment is calculated for every tree species row based on the yield tables used in the NFD. The NFD adds the 10-year period average annual increment to the growing stock data of the previous year for each tree species row and subtracts officially registered annual harvest from this. However, in the DAS model, the total growing stock is recalculated as a function of stand age for every subsequent year. Average increment data are not used to recalculate growing stock. Height is recalculated instead as a function of the age using yield functions by Gál (1980, 1988). Afterwards, the growing stock is obtained from the official NFD yield tables. The harvested volume for thinning and precommercial harvests is not calculated separately because average precommercial extraction and mortality is included in the stock data predicted by the yield tables of Király. The yield table-based processing of the DAS model also allows for modelling the effect of changing climate parameters on stand productivity because the yield class parameters can be changed accordingly over time

2.3 Total area of final harvest as a driver

The model defines the final harvest by the area affected by final harvesting events. Clearcuts, gradual renewal cuttings, and other harvests generating the obligation of forest regeneration are regarded as final harvests. According to our previous examinations, the total final harvest area defined above is quite stable in time and is not closely related to the yield area derived from the cutting ages specified in the forest management plans. It is also independent of fluctuating wood market trends. Since 1990, the area under final harvest has been around 20–23 thousand hectares, with some observable expansion in the last decade.

The present study determined that a significant part of the forest stands is not harvested at the cutting age prescribed in the forest management plans. Historic data series reveal that only two-thirds of stands reaching their cutting age are harvested (Kottek et al. 2023). From this, the study concluded that forest-stand age class structure and forest management plan felling prescriptions do not determine the actual harvest regime in the medium term. Cutting age prescriptions can only be regarded as the potential for harvest, but external factors such as timber harvesting capacities, nature conservation restrictions, forest management purposes, ownership and legal regulations determine actual harvests. 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.

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

The DAS model does not apply the cutting ages that forest management plans predefine to define the cutting age of 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. Japanese forest modelling uses a similar cut parameter dependent on subcompartment age called “Gentanritsu” (or “Gentan”), and it determines the forest area cut at a period (Yoshimoto 1996a,b, Suzuki 2003). The age-dependent harvesting probability ratio distributions used in the DAS model are derived from historic NFD data. Thus, the model does not predefine a forest stand’s final harvest time. Subcompartments with special nature conservation requirements and continuous cover forests are excluded. Subcompartments actually harvested are selected randomly according to their age and area, in line with the age-dependent harvesting probability ratio distributions and the final harvest total area as prescribed in the parameter sheet. The model uses regulatory parameter distributions derived from the country’s forest estate 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. Moreover, management transitions can be modelled. For example, cutting age increases due to nature conservation considerations or cutting age decreases in private production forests due to related regulation changes can be considered. Also, cutting age distributions can be changed to adapt to various scenarios and periods. The model can also adapt to the changing age class structure of forests. If the area of a given age-class accumulates, its forecasted yields also increase. Salvage logging and sanitary felling can also be modelled by incorporating final harvests at younger age classes.

The cutting age distributions are usually not closed, i.e., 100% of the area is not harvested in the last age class affected by the final harvest. This means that some subcompartments are never harvested in the model if they reach the maximum of their cutting age and are not selected for harvesting. 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). However, long-term projections require additional parametrization because such stands may not exist forever. They might collapse, transform or be transformed into continuous cover forests.

2.5 Transition matrix of forest regenerations

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

Figure 1 shows the forest regeneration distribution (i.e. the regeneration transition matrix) of sessile oak *(Quercus petraea)* forest stands as an example.

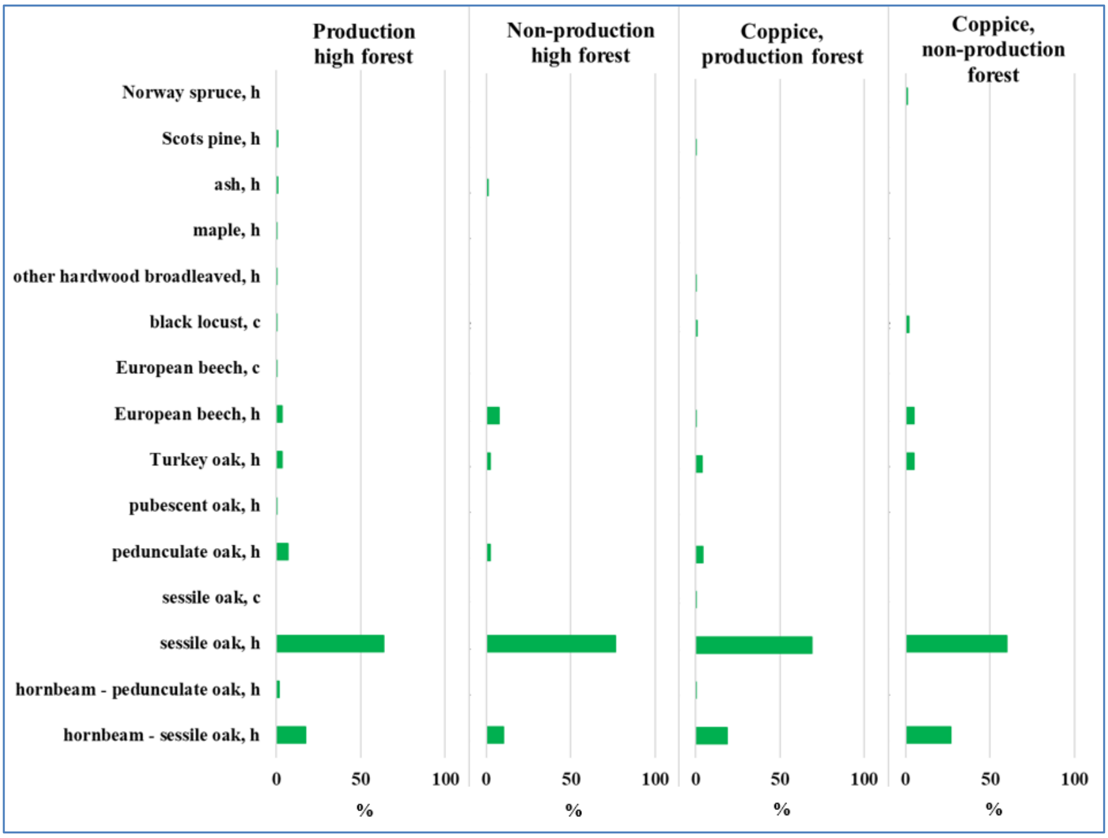

Figure 1. Forest regeneration transition matrix of sessile oak (Quercus petraea) stands (Y axis shows the tree species distribution after regeneration of former sessile oak stands; h: high forest, c: coppice)

Applying the forest regeneration transition matrix in the DAS model makes it possible to change the forest regeneration patterns in time or along different scenarios, allowing for the consideration of changing climatic conditions affecting tree species distribution and modelling of tree species replacements during regeneration.

2.6 Pools of the model

The DAS model uses pools for its processing. The pools are stand-attribute databases of sample forest subcompartments with all their descriptive data normalized to one hectare. The current model version uses three pools: regeneration, afforestation and found forests. Found forests are previously unknown by the Forest Authority and identified during field surveys associated with forest management planning. Found forests can be the result of natural forest area expansion or geodesic re-measurements.

The pools contain historical data of stands under afforestation and regeneration and stand data that entered the NFD as found forests. Stand attributes of subcompartments entering the model as new afforestation or replacing a final cut stand are selected from the pools during the model runs. Forest regeneration selection is driven by tree species, origin, yield class, and county code drive. In afforestation, stand attributes are selected according to the projected afforestation characteristics. The afforested stands enter from the afforestation pool in their completed, afforested state (with data on tree species composition, yield class, etc., stored at that time). For earlier years, data are counted backwards from this state for the estimated year of initial planting.

The afforestation pool contains normalized stand attributes derived from 17 thousand subcompartments with a 78 thousand-hectare area. The regeneration pool contains normalized stand attributes derived from 37 thousand subcompartments, with a 120 thousand-hectare area.

3 EXAMINATION OF CUTTING AGE DISTRIBUTIONS BETWEEN 2006-2021

3.1 Materials and methods

This study examines the cutting age distribution for 2016–2021 and combines it with previously collected data on the cutting age distributions for 2006–2015. The study prepared a new set of species-specific cutting age distributions that can be used for the planned re-run of the DAS model.

The present study collected all subcompartments under final harvest between 2016–2021 from the NFD, grouped the final harvest area by age, species, yield class (1-6) and forest stand function (economic/production forest, and other/non-production forest), and calculated the total area (harvested and not harvested) for each subcategory before harvest. This made it possible to calculate the ratio of the harvested area when compared to the total area in each age class separately for each sub-group by species, yield class, and forest function. The distribution of this ratio by age class describes the harvesting pattern and probability of each subgroup (Suzuki 2003) and can be used for the re-parametrization of the DAS model. In some cases, the ratio was equal to or above 100% due to data quality problems, which arose when very small areas belonged to an age class. In these cases, the study used the average ratio of the two adjacent age classes or 100% in the terminal cutting age class.

3.2 Results and discussion

This paper presents its results using the example of sessile oak (*Quercus petraea*) stands. *Figure 2* and *Figure 3* show the total area of the species for the three examined periods (i.e. 2006–2010, 2011–2015 and 2016–2021) divided into two categories, production forests and non-production forests. In sessile oak, the study observed notable differences between the production and non-production type of forests and presents the results according to this division. When we observed no significant difference between the two subcategories (e.g. pedunculate oak – *Quercus robur*) we created only one cutting age distribution for DAS model parametrization.

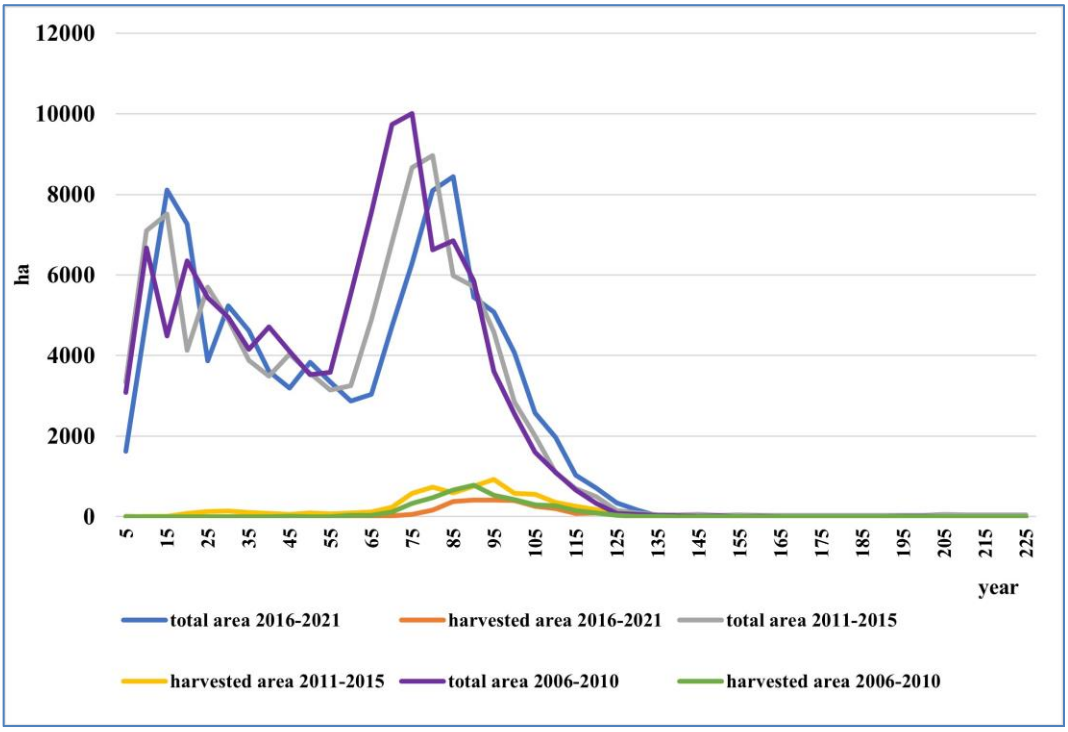

Figure 2. Total area and harvested area of sessile oak (Quercus petraea) production forests as a function of the age expressed in years

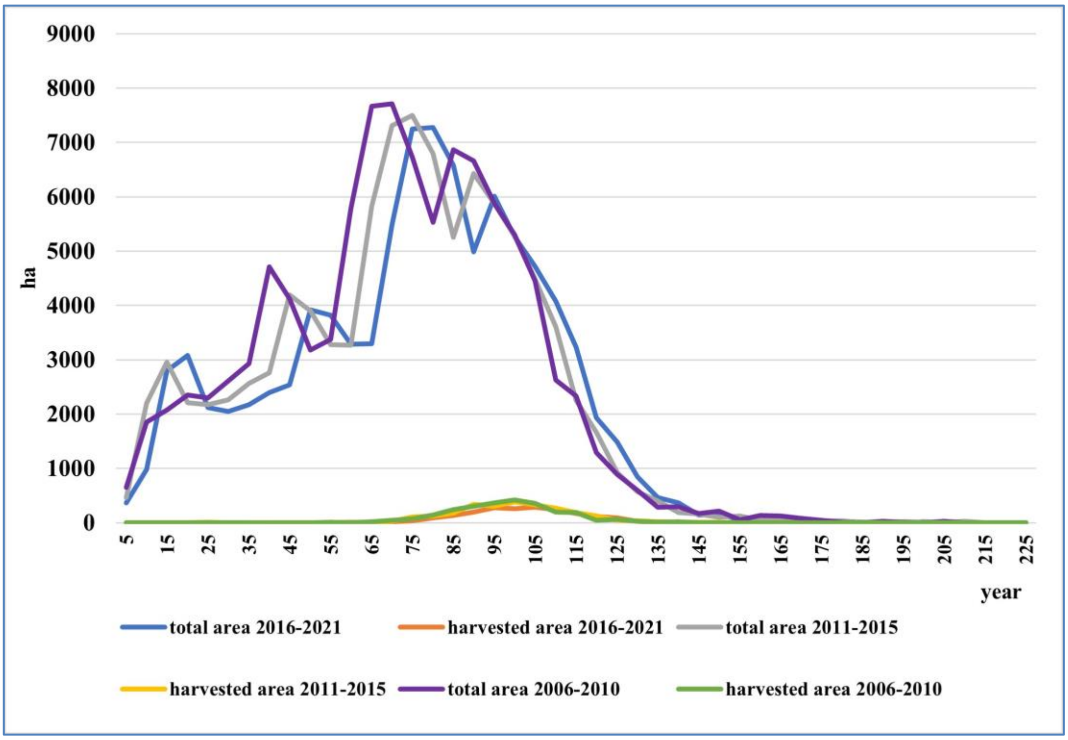

Figure 3. Total area and harvested area of sessile oak (Quercus petraea) non-production forests as a function of the age expressed in years

The figures illustrate that no stand is older than 135 years in the production forest category, while the age range is wider in the non-production forest category, with some stands older than 175 years. Forest functions may be the reason for this as the function of non-production forests relates more to nature, soil protection, and carbon storage. Thus, keeping these forests standing for longer is reasonable. The typical cutting age is also higher in non-production forests, presumably for the same reason. In addition, expensive regeneration in soil protection forests may make final harvests unprofitable. Furthermore, whether regeneration is feasible in the given area is often doubtful.

The age distribution of indigenous species with long rotation periods is quite uneven in Hungarian forests and far from the balanced distribution of normal forests. The current 70-100-year-old age groups are strongly overrepresented, as the example of sessile oak demonstrates. Many forests in Hungary were harvested during and immediately after the two world wars and regenerated afterwards. These forests have now come close to their maturity age (according to the current standards). The increase in cutting age observed in our previous study (Kottek et al. 2023) in the case of indigenous species is, therefore, closely related to the above unevenness of the age class structure. The main reason for rising harvesting ages is the social demand for close-to-nature forest management. This results in the maintenance of older forests as a silvicultural practice. Currently, age class structure provides an opportunity to satisfy this social expectation, which is a very fortunate possibility from a sector policy point of view. Another reason is that forest managers gradually increase the cutting age to equalize yields and evenly distribute regeneration capacities over time. This trend will probably continue as long as the predominance of the older age class persists.

Figure 4 and *Figure 5* show the age-dependent harvesting probability ratio distributions of sessile oak (*Quercus petraea*) production and non-production forests by yield class. In the production forest category harvesting rates are higher than in the non-production forest category. The harvesting probability ratio in both categories decreases from yield class 1 toward yield class 6. It is much more profitable to harvest the stands in yield classes 1 and 2 than in the less productive yield classes. Thus, yield classes 1 and 2 are preferred when selecting stands for the final harvest.

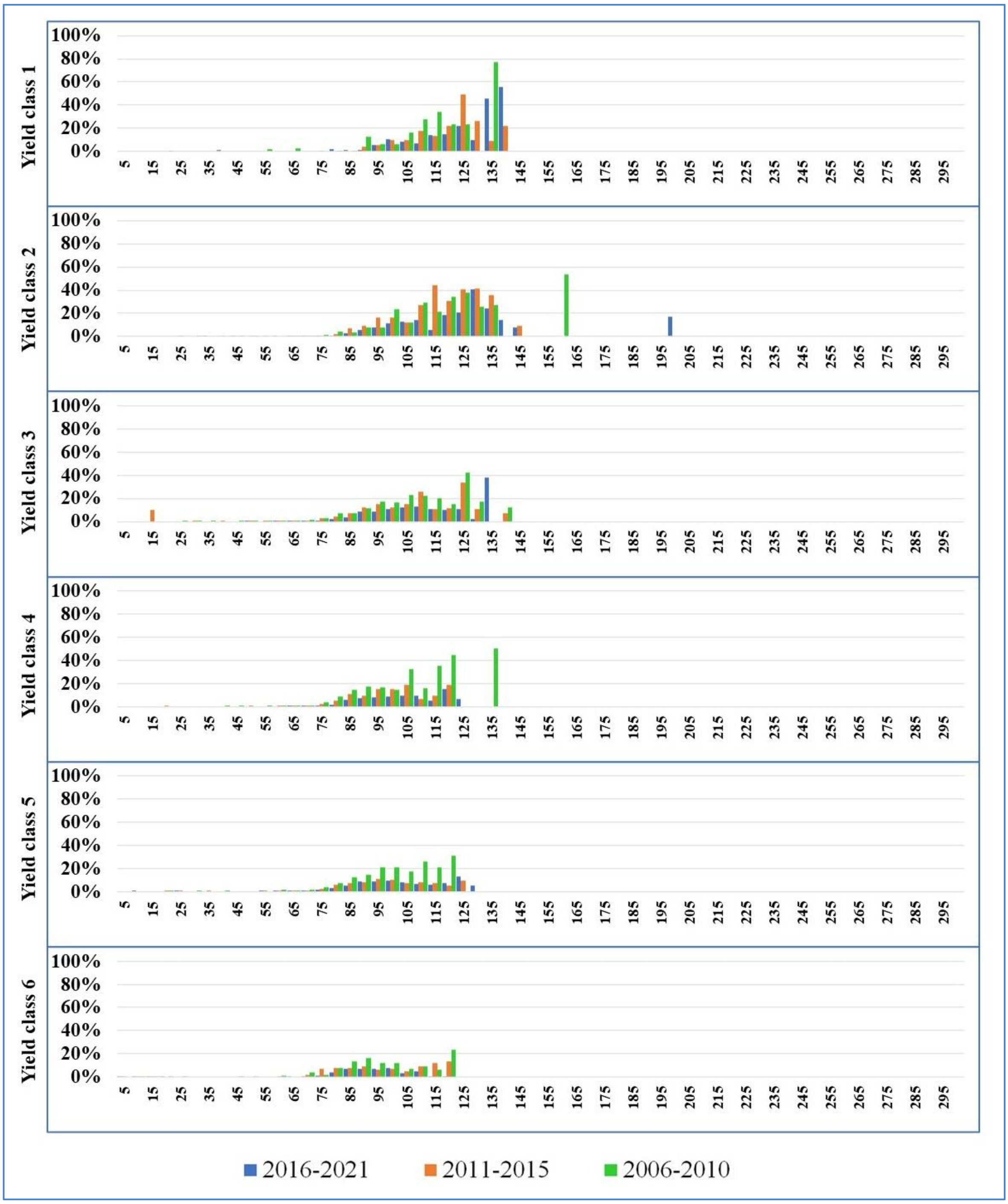

Figure 4. Distribution of age-dependent harvesting probability ratios of sessile oak (Quercus petraea) production forests

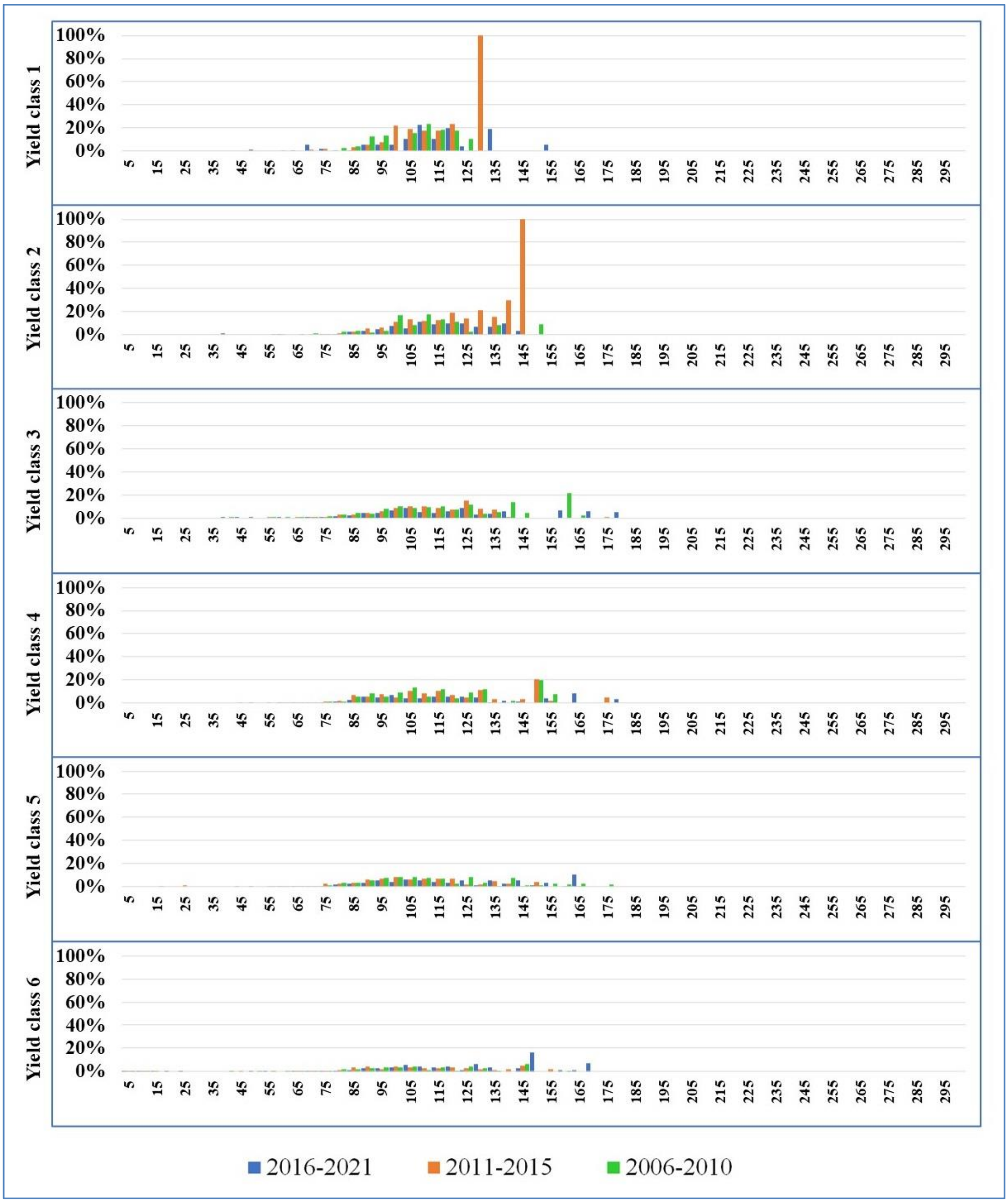

Figure 5. Distribution of age-dependent harvesting probability ratios of sessile oak (Quercus petraea) non-production forests

The same age-dependent harvesting probability ratio distributions shown above were created by yield class for fifteen species groups and production and non-production forests separately where notable differences between the two were observed. The 2011–2021 distribution average was then calculated. The values equal to or above 100% were then filtered out as described in the *Materials and Methods* section and an average age-dependent harvesting probability ratio distribution was created. Our previous study (Kottek 2022, Kottek et al. 2023) observed a decreasing trend in the harmonic mean of the cutting ages in black locust (*Robinia pseudoacacia*) private production forests since the Hungarian Forest Act change in 2017. Since this trend change is significant and can be well explained by the new regulation, the wood market demand, and the financial interest of private forest owners, we narrowed the reference period to 5 years in this case and used only the 2016–2021 dataset for the DAS model parametrization. In all other cases, we used the average age-dependent harvesting probability ratio of the 2011–2021 period. The above applies to the BAU scenario, which assumes that typical management practices of the reference period do not change in the whole projection period. The average age-dependent harvesting probability ratio distributions created this way will be used as parameters during the re-run of the BAU scenario of the DAS model.

4 CONCLUSIONS

This paper presented the DAS forest model, described its main characteristics, and outlined its ability to project standing volume, increment, harvest, and carbon sequestration on the stand, regional or country levels. We described the function of the age-dependent harvesting probability ratio distribution in the modelling process and in determining the selection of subcompartments for the final harvest. We presented our latest results regarding the cutting age distributions of the 2016–2021 period and described the preparation of the new set of species-specific age-dependent harvesting probability ratio distributions prepared for the re-parametrization of the model. Based on the investigation and the method used for selecting the subcompartments for final harvest in the DAS model, the study concludes that the DAS model can adapt to changing age class structure of forests. If the area of a given age class or subgroup of forest stands accumulates during modelling, its forecasted yields and harvests also increase. Stand subgroups can be created per tree species group, ownership, function (production forests and other forests), yield class, or as a combination of these factors. The DAS forest model could also be introduced into forest inventory practice because the model can serve as a procedure package that works very similarly to the NFD. It can be used to derive descriptive data in the short term at a relatively low level of aggregation. This feature also makes the model suitable for describing the probable state of forest stands previously included in the NFD but since removed for some reason. The DAS model can calculate stand attributes as long as there is no data collection about them or only the final cut date is known. In this case, the initial state for the modelling is the last known state as described in the NFD. The model is also suitable for forecasting the state of forests outside the NFD. In these cases, the initial state can be derived from remote sensing or from the systematic forest inventory. However, it should be noted that accurate long-term result can only be obtained if the modelling is supported by remote sensing and periodic field measurements.

We also conclude that the new data on cutting age distributions can be used to actualize the projections made by the DAS forest model and conduct new model runs considering the changes in harvesting patterns. In the framework of the ForestLab project (TKP2021-NKTA-43), we are planning to conduct new studies on the forest regeneration patterns of the 2016–2021 period, renew the forest regeneration matrix of the DAS model, and re-run the projections for 2024–2050.

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