Cent. Eur. For. J. 65 (2019) 145–146 sciendo DOI: 10.2478/forj-2019-0024
CENTRAL EUROPEAN Forestry Journal
http://www.nlcsk.sk/fj/

EDITORIAL

Modelling in forestry sciences, high technologies and decision-support systems in forestry and wood-processing

Dear readers,

We live in an extremely dynamic period characterised by enormous progress in technologies and information in all sectors, including forestry and wood-processing industry. The level of application of information and communication technologies, expert systems, and decision-making systems to the production sphere as well as to the organisational structures of enterprises is in fact considered an important criterion of the company's maturity.

Research in the forestry sector is currently aiming to support the transition to a more sustainable model that will make forests more resilient to the impacts of climate change and that will ensure more efficient use and increased valorisation of resources.

Industry 4.0 (Cyber-physical systems, Internet of Things and Services, Big data, Cloud computing, Artificial intelligence) opens up new pathways to enhance technological and economic development. However, Industry 4.0 concepts need increased and targeted efforts to be adapted in the forest research domain and the forest-based sector, to fully exploit these new opportunities for sustainable forest management and industrial growth.

The main objective of the issue is to provide insights to the state of research related to ICT technologies implementation in the Central European macro-region. It addresses main trends and priorities in three areas: **1) Forest modelling and visualisation; 2) Lidar and satellite remote sensing applications, and 3) Expert and decision support systems in forestry.**

The article ***Forest modelling and visualisation – state of the art and perspectives*** represents a perfect introduction to the first section. It brings an evaluation of the current state of technical possibilities, perspectives of modelling and visualisation of forest ecosystems. In the example of 34 forest models, it demonstrates an integrated approach for model categorisation using a classification scheme. Forest visualisation is described from the point of different visualisation methods and used technologies. Data inputs that are necessary for the models and need to be derived using specialised tools, such as various forms of data generators, are presented, too. Perspectives and challenges for further development of forest models and visualisation technologies were specified as well.

The representative article ***Fir (Abies spp.) stand biomass additive model for Eurasia sensitive to winter temperature and annual precipitation*** is an excellent example of data integration from studies of 272 fir stands in Eurasia and an advanced method of biomass modelling by a three-step proportional weighting additive model disaggregating tree biomass into individual tree compartments. The results indicate that fir seems to be a perspective taxon from the point of its productive properties in the ongoing process of climate change.

Historical radial increment data from the close-to-nature experimental forest management unit in Central Slovakia was used for ***retrospective modelling of changes in forest dynamics*** using an advanced density-dependent matrix transition model. An integrated tool for nonlinear financial optimisation searched for an optimal management equilibrium represented by optimal basal area, tree species composition, diameter distribution and target harvest diameter. The main lesson learnt from the past is not to trust simple extrapolation of current trends, such as the observed continual decline of spruce related to climate change, too much, but to be aware of temporal and possibly reversible processes, such as the observed extensive fir recovery after reduction of air pollution. Tree species diversity appears to be the best option for the uncertain future.

The second section comprises four papers about **close-range photogrammetry, airborne lidar scanning and MODIS satellite data.** Contributions point at the widespread use of remote sensing data to detect tree, stand, ecological and geographical characteristics from a tree level to large-scale applications.

The study ***Predicting forest stand variables from airborne LiDAR data using a tree detection method in Central European forests*** is touching the future**.** It is a nice example of a more accurate estimation of stand characteristics (mean height, mean diameter and total stock) using a strictly scientific method based on new software solutions. Specifically, the multisource-based method, implemented in reFLex software, uses all the information contained in the original point cloud and a priori information.

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Each new technology requires verification of its accuracy, and each increase in accuracy increases the value of new technology. In this sense, the highly valuable study is ***The vertical accuracy of digital terrain models derived from the close-range photogrammetry point cloud using different methods of interpolation and resolutions.*** The research results proved further possibilities and improvements in generating digital terrain models (DTM) using techniques of structure-from-motion and multi-view stereo.

The essence of ecosystem research is their long-term and continuous monitoring. The paper ***Suitability of MODIS-based NDVI index for forest monitoring and its seasonal applications in Central Europe*** demonstrates the multipurpose application of the normalised difference vegetation index (NDVI) derived from MODIS products for forest damage monitoring, forest phenology and increment assessment in relation to climate indices across the macro-region of the Western Carpathians and Pannonian basin.

Wood assessment optimisation should be the top priority of the forestry subjects that are fundamentally dependent on the income from its sale. The paper ***Possibilities of image analysis for quality wood sorting*** compared the classical methodology used in forestry practice with the application of ImageJ software to determine false heartwood and rot. The ImageJ software application led to an improved assessment (transfer to a higher quality class) in 56% of the logs. The analysis therefore confirmed that in the case of a considerable irregularity in a qualitative character (when the surface area of the character significantly differs from the circumscribed circular surface), the standard STN EN 1309-3 methodology systematically overvalues the surface area of this character.

The third section devoted to the research in the area of **expert and decision support systems** covers two papers, which confirm a tendency from description to forecasting and multi-disciplinarity of the solution related to forest management planning and wood marketing.

The first one is focused on ***Marketing support of decision-making at the forest enterprise: A case study on roundwood assortments portfolio.*** The paper compared the most used marketing decision-making models: SWOT, Growth–share matrix BCG and Mckinsey GE matrix with the support of ABC analysis. The outcomes of models contribute to each other and do not contradict. The methods of marketing decision-making models can be applied in managing forest enterprises and they are a great contribution. However, the experience and knowledge of a marketer or a manager are important for the correct interpretation of these models.

Ecosystem services play an important role in the daily life and well-being of millions of people worldwide. The paper ***Multi-objective land allocation for zoning of ecosystem services in mountain forests*** describes and proposes an innovative four-phase workflow of the evaluation of forest ecosystem services and of the zoning of priority areas integrating the knowledge system and analytical functionalities of GIS. Evaluated are erosion control, avalanche control, wood production and cultural services. Techniques of multi-objective land allocation were applied to allocate complementary and conflicting objectives. The non-financial system utilising fuzzy logic for evaluation purposes proved to be appropriate to compare the priorities of individual ecosystem services. A comparison of results with the existing (control) map of ecosystem services has proved that the proposed system is a potent means for multi-objective forest planning.

We thank all authors for their contributions and professional approach to presenting their research areas and the latest trends. We are aware of the fact that the issue of the journal is far from covering the whole range of research and innovation activities related to the implementation of modern technologies in forestry, such as computerisation of analogue reports and records, modernisation of web applications into responsive widely available applications, mobility of field data collection applications etc. In spite of this we believe that the presented issue of the journal will provide the professional public with useful and interesting insights into the current development and the state of informatics and modern technologies in forestry and forest-based industry and thus contribute to further development of our sector.

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Cent. Eur. For. J. 65 (2019) 147–165 sciendo DOI: 10.2478/forj-2019-0018
CENTRAL EUROPEAN Forestry Journal
ORIGINAL PAPER
http://www.nlcsk.sk/fj/

Forest modelling and visualisation – state of the art and perspectives

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Abstract

The paper provides a detailed overview on forest models from various perspectives. The presented classification scheme of forest models uses concept, object, space and time as variables to place models in specific categories and thus provides an integrated approach for model categorisation. A short description of individual categories with the examples of models helps to understand their nature. In total 34 forest models were classified according to the created scheme. Forest visualisation has also an important place in forest modelling. Here it is described from the point of different visualisations methods and used technologies. Inputs that are necessary for the models but are often not available and need to be derived using specialised tools – various forms of data generators are presented too. Important perspectives and challenges of further development of forest models and visualisation technologies were specified as well.

Key words: simulations; prognostic tools; virtual reality; hybridisation; input variables

Editor: Dimitrios Panagiotidis

1. Introduction

Current forestry is marked by global climatic and socio-economic changes. Climate change reflected by increased weather variability and more frequent occurrence of extreme events (disturbances) causes changes in forest production, structure, and health (Seidl et al. 2017). Socio-economic changes affect the use of forests towards the expansion of ecosystem services. Planning of forest management now concerns a wider range of interest groups (state, forest owners, non-governmental organisations, and the public). Forest management is not only geared to wood production but also to carbon sequestration, which helps to reduce the rate of climate change, to biodiversity promotion as it increases the resilience and sustainability of ecosystems, as well as to improved quality of people's lives by protecting water and land, by enhancing the recreational function of forests, etc. These changes have a global cross-border character. This requires changing planning procedures and tools, as planning at such a scale is not possible without a tool for predicting forest development.

Yield tables have been frequently used for forest management planning purposes. However, they are currently not able to fully satisfy demands due to the following reasons. Yield tables are intended for even-aged mono-species stands managed using a pre-defined approach and site classification typical for a specific country/region (Assmann & Franz 1963). They provide only a limited range of applications due to: i) differential management aiming at the preference of mixed, uneven-aged and spatially structured forest stands, ii) diversification of treatments (for example thinning) to regulate ecosystem services, iii) response to climate change and forest disturbances, iv) needs for a diversified range of outputs. Forest inventories based on new technologies, such as terrestrial and aerial laser scanning, terrestrial and aerial photogrammetry, field GIS mapping, unmanned vehicle applications, remote sensing methods, have recently been developed (Liang et al. 2016; Mohan et al. 2017; Puliti et al. 2017). Modern approaches provide a range of data that far exceeds inputs to yield tables and shifts planning opportunities towards precise forestry (tree-level planning). This necessarily involves the need for corresponding forest models. Presented study is concentrated on the review of existing forest model categories, and their potential to solve different planning issues regarding their modelling scale. In the second part, we analyse forest visualisation methods and tools as effective expansions of forest models for interpretation of forest development.

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2. Current status in forest modelling and visualisation

2.1. Variables and parameters of forest models

Forest models are applied to forests of interests by **forest simulators**. Forest simulators reproduce the behaviour of forest ecosystems in the form of a computer program (Fabrika & Pretzsch 2013). Figure 1 shows a scheme of a simulator. A simulator is a unification of the system environment and the system itself described by the model. The system reacts to the environment and influences it in return. The model contains **system parameters**. System parameters are constant values which control the model. They include various equation coefficients or ecophysiological constants derived from empirical measurements or biological studies. They do not change during a simulation and remain constant even if the simulated object changes, e.g. the forest stand. The current status of the system is described by **state variables**. State variables change during a simulation and represent main variables of the system. They are input system variables since they describe the initial state of the system, and at the same time, they are output variables because they describe its development. For example, they define tree dimensions or stand variables. A change of state variables is influenced by the model which is controlled by its system parameters. At the same time, the development of state variables also reacts to **exogenous and intermediary variables**. Exogenous and intermediary variables express the state of the system environment, e.g. climate. Whilst exogenous variables are not influenced by the system, intermediary variables change depending upon the system state. Exogenous variables are therefore related more to the macroclimate (temperature, precipitation), and intermediary variables are more related to the microclimate (light in the stand). Exogenous variables control the model and intermediary variables regulate the model. We can therefore state that the model reacts to the environment (exogenous and intermediary variables), changes the system state (state variables) or in return, the system influences the environment (intermediary variables). The environment controls the system dynamics via exogenous variables and regulates the system state via intermediary variables.

2.2. Classification of forest models

Current literature provides a wide selection of models, which vary not only in their principles and algorithms, but also in their software design. The basic classification of models based upon the modelling concept (Kurth 1994) distinguishes empirical, process-based and structural models. Other approaches classify models according to their temporal-spatial hierarchical level (Pretzsch 2001), object-spatial hierarchical level (Lischke 2001), or other principles (see e.g. Munro 1974; Shugart 1984; Vanclay 1994; Liu & Ashton 1998; Houllier 1995; Franc et al. 2000; Porte & Bartelink 2002; Pretzsch 2009). The description of the character of individual classifications can be found in monographs dealing with forest modelling, e.g. Pretzsch (2009); Weiskittel (2011); Burkhart & Tomé (2012) or Fabrika & Pretzsch (2013).

For this study we chose the classification of Lischke (2001), which was modified by Fabrika & Pretzsch (2013) and subsequently simplified to its current form (Fig. 2). According to this classification, models can be divided into categories based on several aspects:

a) **A concept** of forest modelling can be empirical, process-based or structural. Empirical models use statistical relationships (such as regression equations) derived from data gathered at inventory or research plots. The principle of a representative sample is applied, and the models are then generalised

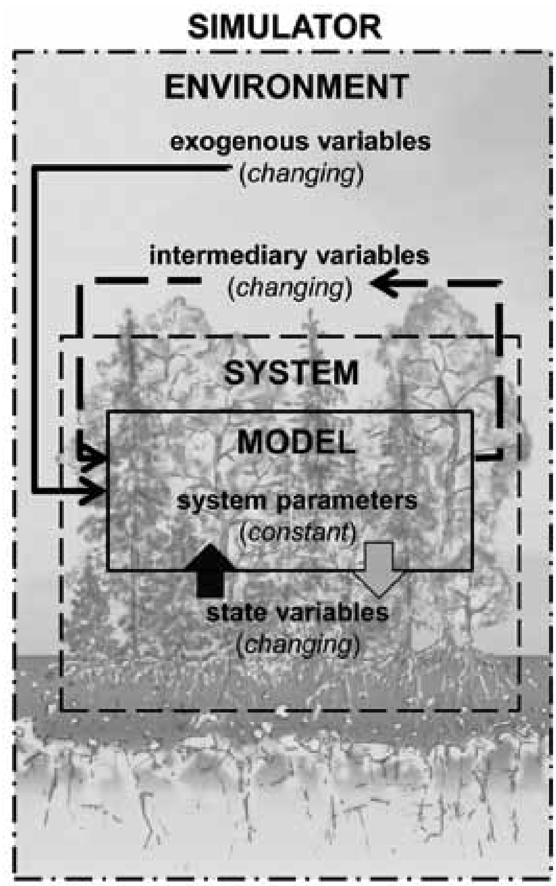

Fig. 1. A simulator, its variables and parameters. The model is controlled by system parameters. It reacts to the surrounding environment (exogenous and intermediary variables), changes the system state (state variables) or in return, it influences the environment (intermediary variables). The environment controls the system dynamics via exogenous variables and regulates the system state via intermediary variables. The black arrows indicate the inputs into the model and the grey arrow indicates the output from the model. The solid thin arrow represents the control of the model and the dashed arrows show the regulation of the model. The thick arrows change the system state (processed by Fabrika & Pretzsch 2013, page 196).

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for the statistical population the sample represented. Process-based models utilise algorithms that exploit causal relationships known from eco-physiological processes (photosynthesis, respiration, allocation, etc.). They are more general. Structural models predict development of tree morphology, such as a stem, branches, foliage, flowers or fruits. They use, e.g. the principles of fractal geometry, growth grammar and computer graphics.

b) An object of forest modelling may be oriented to organs (e.g. leaves), organisms (e.g. trees), classes/cohorts (e.g. diameter classes), populations (e.g. forest stands) or ecosystems (e.g. biomes). An object is the principal modelling element represented by state variables that describe its state and change in time. For example, if the modelled object is a tree, it is represented by its diameter, height and volume, while if the object is a forest, its state variables are mean diameter, mean height and growing stock (volume) per hectare.

c) Space of the forest modelling may be represented by a 3D position, 2D position, bio-group, stand, or a region. It specifies in which spatial unit the environment, i.e. exogenous and intermediate variables, changes. The environment refers to the conditions that affect the spatial dynamics of a modelling object, such as the amount of light, climatic conditions, soil conditions, or the competitive pressure. They may be different in the three-dimensional space (x, y, z), or they may change only in the horizontal space (x, y), or from one bio-group to another, from one stand to another stand, or from one region to other region.

d) Time of the forest modelling expresses an elementary time unit, for which the changes of the state of the modelled object are shown. It can be minutes, hours, days, years, 5-year intervals or decades, centuries or millennia.

Figure 2 shows the classification of forest models that considers all above-defined aspects of forest growth modelling (Fabrika & Pretzsch 2013). Due to its resemblance with chess, we call it a "chessboard of models". It shows 10 well-known categories of forest models:

1) Eco-physiological tree models (αI) simulate causal processes (Landsberg & Sands 2011). Assimilation in foliage of individual trees is their basic modelled feature. Individual leaves or needles can be modelled as separate objects or more frequently as generalised objects in the form of solids of a tree crown or its layers. The position of these objects in 3D space of a stand is important for the level of radiation absorption calculated using different approaches, e.g. the method of ray-tracing (Brunner 1998). The result of the production is net biomass that is allocated into tree organs. Pfreundt (1988) was the pioneer of the described modelling principle, and Hauhs (Hauhs et al. 1995) was the first person who used this principle for forest modelling and developed TRAGIC model. From newer models we can name e.g. BALANCE model (Grote and Pretzsch 2002; Rötzer et al. 2009).

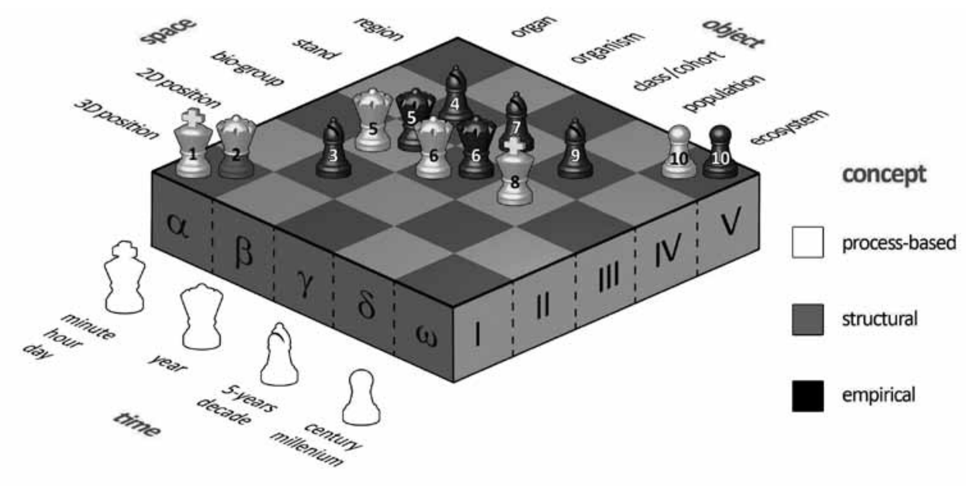

Fig. 2. Classification of models according to object, space, time and concept. Object describes character of state variables changing during simulations. Space describes location of environmental variables (exogenous and/or intemediary) varied in area. Time describes temporal interval for changing of state variables during simulations. Concept describes algorithmic principle of the model. In recent times, the classification has defined 10 categories of models: eco-physiological tree models (1), functional-structural plant models (2), empirical distance-dependent tree models (3), empirical distance-independent tree models (4), tree gap models (5), cohort gap models (6), distribution models (7), big leaf models (8), stand models (9) and biome models (10). The position on a chessboard classifies a model on the base of a modelling object and spatial resolution. Temporal resolution is expressed by type of the figure. The color defines a dominant concept. Future development may fill other positions of the "model chessboard" (processed by Fabrika & Pretzsch 2013, page 206).

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2) Functional-structural plant models (αI) deal with modelling the development of plant morphology in time and space. Their foundations were laid by Prusinkiewicz based on the ideas of Lindenmayer (Prusinkiewicz & Lindenmayer 1990). The models are based on growth grammars (morphemes), which define recurring replacement of tree parts with new parts in a recursive manner. In this way, branching structures (graftals) are created, and are displayed using vector (turtle) graphics. Hence, they originate in the fractal geometry and the so-called L-systems. The shape and the size of new plant structures depend on eco-physiological processes, in particular photosynthesis, which are directly built in growth grammars. As an example, we can name GROGRA (Kurth 1999); LIGNUM (Perttunen et al. 1998) or GroIMP (Kniemeyer 2008) products.

3) Empirical distance-dependent (spatially explicit) tree models (βII) are based on empirical relations between tree increment (on diameter, height or volume), environmental conditions (e.g. site index of a stand, or a set of site conditions), and competition pressure on a tree. Competition pressure is simulated using competition indices dependent on the position and dimensions of the surrounding trees. The foundations of this approach were laid by FOREST model (Ek & Monserud 1974). From newer models we can mention e.g. SILVA (Pretzsch et al. 2002; Pretzsch 2009) model.

4) Empirical distance-independent (spatially non-explicit) tree models (βIV) are of a similar character but modelling of tree competition is not dependent on tree co-ordinates. The competition pressure is derived using the total area (canopy cover or density) or tree position within the cumulative frequency function of the selected biometric characteristic. This simplified approach of modelling competition was introduced by Wykoff et al. (1982) in the STAND PROGNOSIS MODEL. From later models we can mention PROGNAUS (Sterba 1995) or BWIN (Nagel 1996).

5) Tree gap models (βIII) divide the area of interest into bio-groups of trees (generally covering from 100 to 1,000 m^2). They focus on modelling the growth of individual trees in bio-groups. Biometric characteristics of trees (e.g. diameter, height) in groups are known. Tree positions are not taken into account, but the positions of bio-groups within the stand are important because they determine the dynamics of the vegetation (succession) in the modelled forest. From the pioneers of this modelling principle we can name Botkin et al. (1972) and their JABOWA model, or FORET model by Shugart & West (1977). From newer products we can mention e.g. PICUS (Lexer & Hoenninger 2001).

6) Cohort gap models (γIII) assume that trees in bio-groups are divided into so called cohorts, which represent generations of trees characterised by distinctive heights. Every cohort is represented by a mean tree and the number of trees. Only the growth of a typical tree representing a specific cohort is simulated, which saves computing time without a significant impact on simulation results. During simulations, trees do not change their memberships in cohorts. Hence, tree number in a specific cohort can only be reduced due to mortality. A model of this category was first created by Bugmann (1994), who proved that the trees similar in size at the beginning of the simulation remain similar during their entire lives. Bugmann applied this approach in his model called ForClim (Bugmann 1996).

7) Distribution models (γIV) simulate forest growth dynamics on the base of frequency dynamics of a selected biometric parameter. In this category of models, an entire forest stand is divided into classes of a specific characteristic, e.g. diameter. Classes do not change in time, but trees change respective classes as they grow. This differentiates these models from the previous group, where cohorts act as classes, the size of which can change, but the membership of trees in cohorts remains constant. The simplest way of modelling is changing the frequency function during time by modifying parameters (Clutter 1963; von Gadow 1987). Other possibilities are to use distribution models based on differential equations (Moser 1974), or Markov Decision Process models (MDP, e.g. Sloboda 1976; Suzuki 1971; Buongiorno 2001).

8) Big leaf models (δIII) generalise assimilation organs in the form of an abstract leaf, which represents the whole spatial unit of an ecosystem, e.g. 1 m^3. The assimilation of an abstract leaf is identical to the performance of a modelled population in a spatial unit. These models assume that the spatial unit is homogeneous from the point of its tree crown cover and represents a certain type of vegetation. Radiation absorption is solved on the basis of leaf area index of the homogeneous crown cover, e.g. using Lambert-Beer law that is sometimes combined with Campbell method of ellipsoid orientation of assimilation organs (Campbell 1986, 1990). The basic representatives of this category are models 3-PG (Landsberg & Waring 1997) or Biome-BGC (Thornton 1995).

9) Stand models (δIV) represent most traditional models that represent the entire population or a species in a forest stand. They simulate the development of mean tree and stand parameters (e.g. mean diameter, mean height, growing stock) on the base of a site index. They are derived exclusively from empirical regression models that are frequently based on growth functions. Their beginnings go back to yield tables (Assmann & Franz 1963; Hamilton & Christie 1973; Vuokila 1966; Schmidt 1971; Lembcke et al. 1975; Halaj et al. 1987). These models have a limited validity for a specific stand type, stand density, and forest management regime. More flexible models of this type are STAOET (Franz 1968) and DFIT (Bruce et al. 1977).

10) Biome models (ωV) assume that the occurrence of vegetation types (biomes) depends on environmental conditions (e.g. temperature and precipitation). They deal with changes of climax vegetation types over long time periods (centuries to millennia). The first and nowa-

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days the classical representative is the model by Holdridge (1947). From newer models we can mention e.g. BIOME (Prentice et al. 1992) or DOLY (Woodward & Smith 1994).

The 10 above-mentioned categories of models can be considered as the basis, from which further possible modifications can be derived. The position of the type in the classifications is marked with their typical position, some variations may however occur outside their typical position. The same is true for the colours of marks in the classification, which represent the modelling concept. In the classification we chose the prevailing concept for a given type of models (Fig. 2). However, model categories may also use other concepts.

The current trend in modelling is **hybridisation**. Hybrid models combine several categories of models. They are mutually complementary, i.e. their algorithms are mutually bound. Another trend is to use **downscale** or **upscale** procedures, which enable shifts from a more general modelling level to a more detailed level (downscale) or vice versa from a more detailed level to a more general level (upscale) using a serial approach. The second procedure is more frequent (see works by King 1991; Rastetter et al. 1992; Bugmann et al. 2000; Dieckmann et al. 2000, Auger & Lett 2003; Urban 2005; Lischke et al. 2006). In addition, a parallel approach of a **multi-scaling** type can also be applied, when one product uses several types of mutually unbound models in parallel, which are selected depending on the purpose of simulations, as it is e.g. in the current version of SIBYLA model (http://sibyla.tuzvo.sk).

The presented model classification is not only versatile, but also open. This means that, if in science or practice the need for a new category of models is identified, a new position of a given colour mark can be put on a particular square of the classification. A similar principle has been applied for the current development of forest models. For example, the first position (δIV) was filled with yield tables and so far, the last position (αI) was occupied with eco-physiological tree models and functional-structural plant models.

We reviewed 34 models from the point of the applied concept, modelled object and space, and used temporal resolution. We found that currently the majority of models combine approaches, i.e. they use different concepts for modelling different processes and simulate different processes at different spatial and temporal scales. This indicates that most current models are hybrid. Therefore, when applying the classification presented above (Fig. 2) we focused on biomass production to enable inter-model comparison. As can be seen from Table 1, most reviewed models (67%) utilise a process-based modelling concept, while the empirical concept was used only in 9 models (26%), and the structural concept in 2 models (6%). Although the selection of models was not performed systematically but was influenced by authors´ knowledge and experience in forest growth modelling, we assume that the distribution of the models in individual concepts reflects the actual state in modelling forest growth.

From the point of the modelled object, in the reviewed models we identified all levels presented in Fig. 2, although the frequencies were unevenly distributed. The levels of an individual tree and a class/cohort were most frequently used (each in 35% of reviewed models), while an organ or an ecosystem were used least often (only in 3 models each).

Similarly, we found all spatial resolutions identified in Fig. 2 that were unevenly represented in the group of reviewed models. The majority of models (41%) operate at a stand scale, followed by a bio-group, which was a characteristic spatial resolution in 35% of models (Table 1). The level of a region was used only in one model, and the positions of individuals in 2D or 3D space were included in 4 and 3 models, respectively.

We found that a class versus a bio-group (position γIII in Fig. 2) was the most frequent combination of an object and space used in nine reviewed models (26%). This combination represents cohort models (Fig. 2). When examining these nine models more closely we found out that the majority of them operate at grid cells, i.e. they are often used for landscape modelling. These models simulate different processes at different temporal and spatial levels, often including interactions between individual cells.

From the temporal point of view, the shortest identified time step was one minute and the longest was 5 years, while a day was the most prevailing time step applied in 11 models (Table 1). Some models operate at multiple time scales depending on the process they simulate, e.g. ANAFORE (Deckmyn et al. 2008) or iLand (Seidl et al. 2012).

Applied dimensions of the classification specify the conditions under which the usage of models is suitable. For example, models operating at long time steps are not able to capture intra-annual changes. Thus, they are not suitable for short-term studies of e.g. extreme climate events, such as drought. Inter-tree competition can only be considered in the models simulating individual trees in a forest stand. Models operating at a coarser spatial resolution can provide us with the information about the forest as a whole, but are not able to describe the specific development of every tree with regard to its surrounding. The applicability of each model in a specific situation depends also on other model characteristics that were not discussed here, mainly on what processes are simulated with the model and what approaches are used for their simulations.

2.3. Classification of methods and tools for forest visualisation

Several authors have addressed the issue of classifying techniques and approaches in forest visualisation

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Table 1. List of reviewed models.

Model	Object	Space	Time	Concept	References
3D-CMCC-FEM	class / cohort	bio-group (grid cell)	day	process-based	Collalti et al. 2014
3PG-BW	population	forest stand	month	process-based	Landsberg & Waring 1997
4C	class / cohort	forest stand	day	process-based	Bugmann et al. 1997
ANAFORE	class / cohort	bio-group	day	process-based	Deckmyn et al. 2008
BALANCE	Organ	3D position	day	process-based	Rötzer et al. 2010; Rötzer et al. 2012; Grote & Pretzsch 2002
BASFOR	population	forest stand	day	process-based	Van Oijen et al. 2005
Biome-BGC	population	bio-group	day	process-based	Thornton et al. 2005
BWIN	Organism	forest stand	5 years	empirical	Nagel 1996
CARAIB	ecosystem	bio-group (grid cell)	day	process-based	Warnant et al. 1994
CASTANEA	population	forest stand	hour	process-based	Dufrêne et al. 2005; Guillemot et al. 2016
CENTURY	ecosystem	forest stand	month	process-based	Parton et al. 1987; Allister et al. 1993
Community Land Model (CLM4.5)	class / cohort	bio-group (grid cell)	30 min	process-based	Oleson et al. 2013; Fan et al. 2015
CoupModel	class / cohort	forest stand	minute	process-based	Eckersten & Jansson 1991; de Willigen 1991; Jansson & Karlberg 2004; Svensson et al. 2008
ED2	class / cohort	bio-group (grid cell)	hour	process-based	Medvigy et al. 2009; Hurtt et al. 2013
FOREST	Organism	2D position	year	empirical	Ek & Monserud 1974
ForGEM	Organism	Region	hour	empirical	Kramer et al. 2008; Kramer & Werf 2010; Kramer et al. 2015
FORMIND	Organism	forest stand	day	process-based	Bohn et al. 2014
GO+	Organism	forest stand	hour	process-based	Loustau 2010
GO+TreeStabd	Organ	forest stand	30 min	structural + process-based	Loustau et al. 2005
GOTILWA	class / cohort	forest stand	hour	process-based	Shinozaki et al. 1964; Keenan et al. 2009;
Heterofor	Organism	forest stand	hour	empirical	Jonard & André 2018
iLand	Organism	2D position	day	process-based	Seidl et al. 2012
LANDIS-II	class / cohort	bio-group (grid cell)	year	process-based	Scheller et al. 2011
LandscapeDNDC	class / cohort	bio-group (grid cell)	minute	process-based	Grote 1998; Grote et al. 2011; Grote & Reiter 2004;
LIGNUM	Organ	3D position	year	structural + process-based	Sievänen et al. 2008; Perttunen et al. 1998
LPJ-GUESS	class / cohort	bio-group	day	process-based	Smith et al. 2001; Sitch et al. 2003; Smith et al. 2014
MOSES	Organism	2D position	5 years	empirical	Hasenauer 2006; 1994
ORCHIDEE-CAN	class / cohort	bio-group (grid cell)	day	process-based	Naudts et al. 2015
PICUS	Organism	forest stand	year	process-based	Lexer & Hönninger 2001; Seidl et al. 2007; Seidl et al. 2009; Seidl et al. 2005
PnET	ecosystem	bio-group	month	empirical	Aber & Federer 1992
PROGNAUS	Organism	forest stand	5 years	empirical	Sterba 1995
SIBYLA	Organism	3D position	year	empirical (semi-empirical)	Fabrika 2005; Fabrika & Ďurský 2006; Fabrika & Pretzsch 2011
SILVA	Organism	2D position	5 years	empirical (semi-empirical)	Pretzsch et al. 2002; Pretzsch 2009
TreeMig	class / cohort	bio-group (grid cell)	year	process-based	Lischke et al. 2006; Bugmann 1994

Note: Object describes character of state variables changing during simulations. Space describes location of environmental variables varied in area. Time describes temporal interval for changing of state variables during simulations. Concept describes an algorithmic principle of the model (see Fig. 2).

(e.g. Orland 1992, 1997; McGaughey 1997; Buckley et al. 1998; Karjalainen & Tyrväinen 2002; Fabrika & Ďurský 2005; Pretzsch et al. 2007). Over the last 20 years, significant progress in **visualisation methods** has been achieved. Today several visualisation techniques are available (Fig. 3). Trees and stands can be displayed in the form of geometric models (1) as horizontal projections (1a), vertical profiles (1b), three-dimensional projections (1c), rendered scenes (1d), or in the form of virtual reality (1e). Another possibility is to use billboard models (2). They represent approaches, when an image of a tree or other forest objects is projected onto a plane surface. The surface can be simple (single-panel models, 2a) or composite (multi-panel models, 2b). Images are most frequently in the form of textures with transparent background, and panels can be interactively rotated towards the observer. Another alternative is to use photographic models (3), which faithfully display forest reality. They can be implemented as snapshot models (3a), sightseeing models (3b), or virtual tours (3c). Forest visualisation uses different methods depending on the scale (Fig. 3). Models can represent a plot (I), a stand (II), or landscape (III). The selection of the scale depends on the chosen detail. A more detailed description of visualisation methods can be found in Fabrika & Pretzsch (2013).

Intensive development of information technologies in recent decades has created conditions for the development of still smarter visualisation hardware. These devices are aimed not only at improving the optical perception of a user, but they also develop new ways of interaction with a virtual environment and address the issues of recording user´s motion transferred to virtual reality. Important technological characteristics of modern **visualisation tools** are presented in Fig. 4. According to used projection methods (A), systems can be cubic (A1), cylindrical (A2), spherical (A3), or planar (A4). Depending upon used projection technologies (B), systems are divided into those realised through projectors (B1), displays (B2) or HMD equipment (B3). According to the character of perception (C), systems can either be with (C1) or without (C2) stereoscopic perception. From the point of immersion level (D), systems can be with partial (D1) or full (D2) immersion. Considering movement in virtual reality (E), systems can be based on devices (E1) or on natural movement (E2). Based on the number of users (F), systems can be created for one (F1) or more (F2) users. Hence, the final solution is given by a combination of various aspects. Currently, a number of different solutions are available, e.g. CAVE systems (Cruz-Neira et al. 1993; Defanti et al. 2009) [A1 + B1 + C1/C2 + D1 + E2 + F2], CAVE2 systems (Febretti et al.

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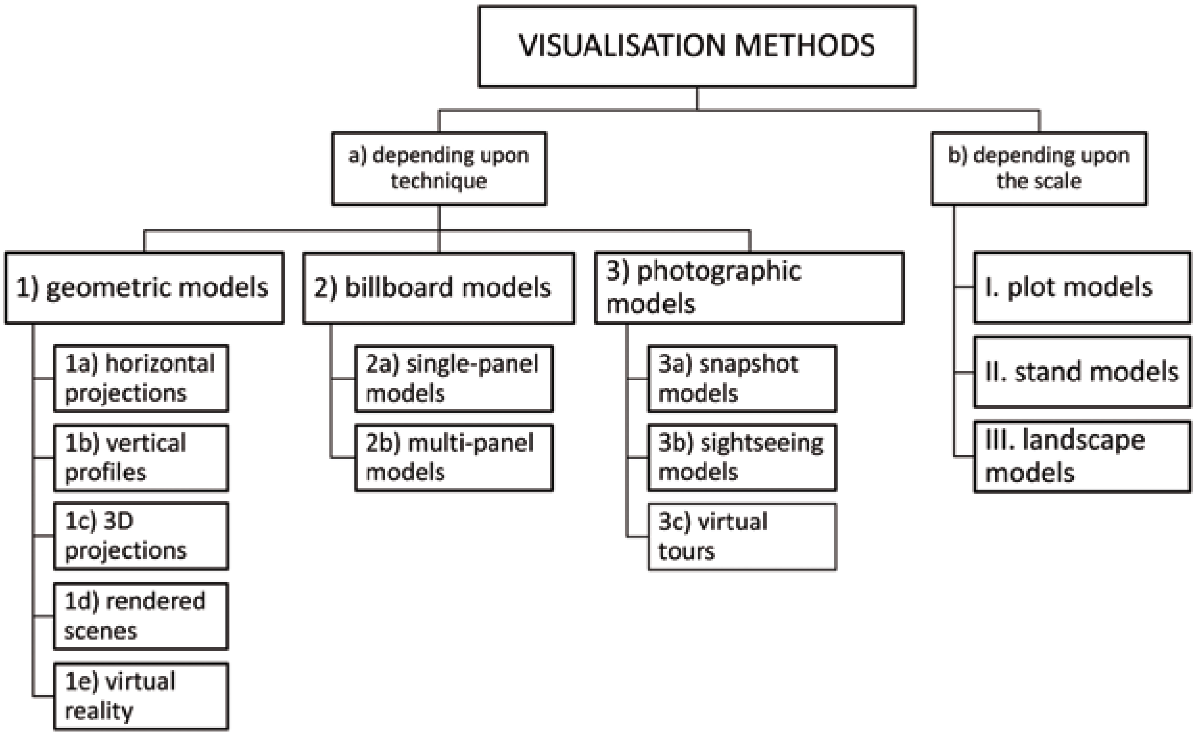

Fig. 3. Classification of forest visualisation methods according to: (a) techniques, (b) scale.

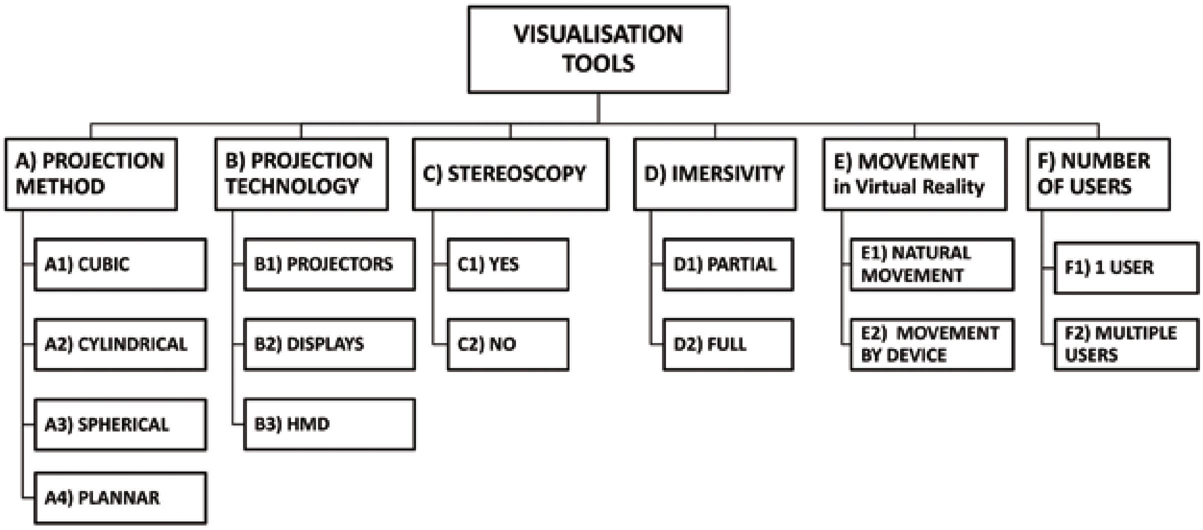

Fig. 4. Categorisation of hardware tools used for forest visualisation on the basis of their technological solutions.

2013) [A2 + B2 + C1/C2 + D1 + E2 + F2], HMD systems - Head mounted display (Oculus 2017) [A4 + B3 + C1 + D2 + E1/E2 + F1], and Virtusphere (Virtusphere 2017) or Cybersphere systems (Fernandes et al. 2003) [A3 + B1/B3 + C2/C1 + D1/D2 + E1 + F1]. To simulate natural movement of a user, various specialised systems are nowadays used, e.g. Cyberith Virtualizer (Cyberith 2017) or Virtuix Omni (2017). For tracking user´s position, optical cameras (e.g. Vicon Bonita 2017) or magnetic sensors (e.g. Polhemus 2017) are most frequently used.

2.4. Tools for generating, reproduction and reconstruction of missing or unknown input variables

As the modelling detail increases, the set of input data also increases. Considering temporal, economic, methodological and technological limits for the acquisition of input data, models often comprise auxiliary tools, which derive more detailed input from commonly available or more general data. This saves time and costs even if it is at the expense of output accuracy. With this

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Fig. 5. Example of forest visualisation via OCULUS Rift device (photo: Peter Valent, 2017).

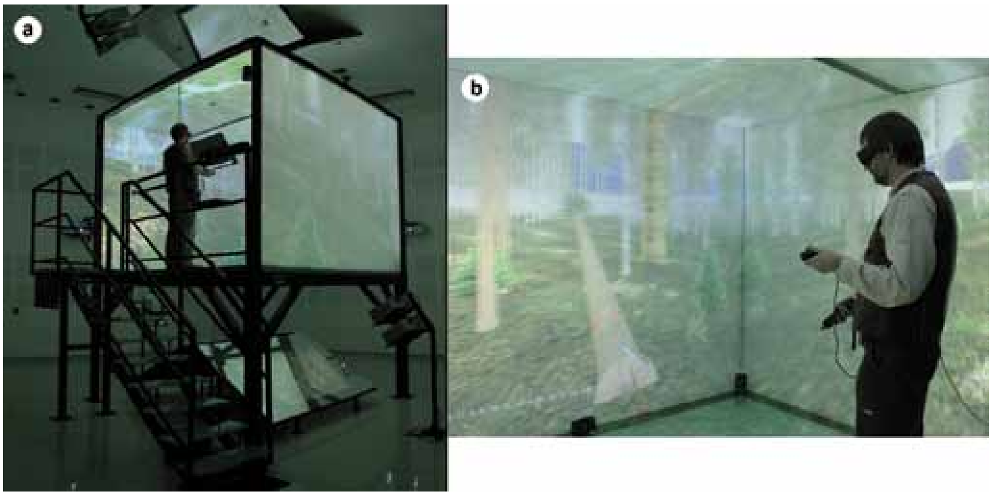

Fig. 6. Example of CAVE device (a) and visualisation of a virtual forest stand with tree interaction (b) (photo: Peter Valent, 2017)

approach we can also derive missing or unknown data necessary for forest modelling with a selected model type (Fig. 2). As an example, we can name various interfaces for forest inventories, tools for structure reconstruction and reproduction, structure generators, site generators, weather generators or models for the numerical weather prediction (Fig. 7).

An interface bound to **forest inventory outputs** contains various computer procedures and algorithms, which can provide or derive necessary data from available inventory databases or geographic information layers.

Tools for **structure reconstruction** are connected to special methods of field data collection, such as field GIS sets (Černý & Bukša 2005), terrestrial laser scanning (Simonse et al. 2003; Aschoff et al. 2004; Heurich et al. 2004; Hopkinson et al. 2004; Pfeifer et al. 2004; Bienert & Scheller 2008; Klemmt & Tauber 2008; Koreň et al. 2017) or remote sensing methods, e.g. aerial photogrammetry (Gougeon 1995; Dralle & Rudemo 1997; Brandtberg 1999, 2002; Gitelson et al. 2002; Surový et al. 2004), aerial laser scanning (Magnussen & Boudewyn 1998; Harding et al. 2001; Persson et al. 2002; Popescu et al. 2002; Heurich et al. 2003; Lim et al. 2003; Blaschke et al. 2004; Clark et al. 2004; Holmgren & Persson 2004), etc. The aim of these procedures is to derive (reconstruct) parameters of objects from obtained data layers or survey materials, e.g. to derive the position of trees or their biometric parameters (diameter, height, crown parameters), or for some types of models to reconstruct the morphology of stems or tree crowns.

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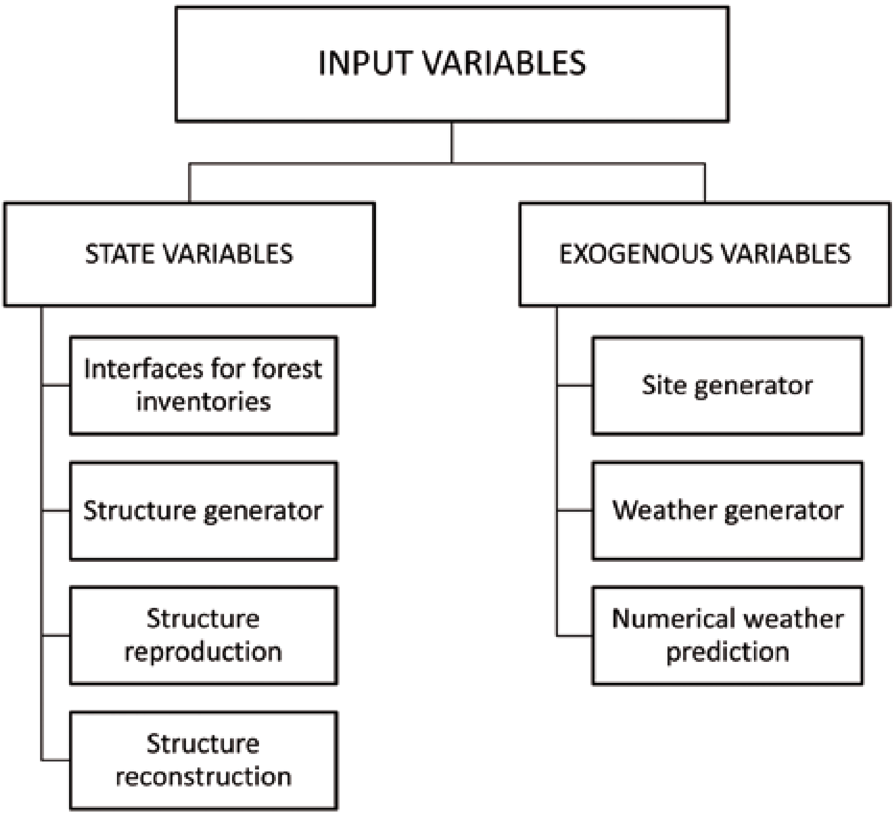

Fig. 7. Tools for deriving more detailed input data for forest growth models from commonly available or more general data.

Forest **structure generators** were developed in order to generate more detailed data from more general data, e.g. to generate tree diameters, tree heights, crown parameters and position of trees from the information about mean diameter, mean height and growing stock, or stand basal area. For structure generation, the methodologically proved approaches (Nagel & Biging 1995; Merganič & Sterba 2006), which ensure that the values of more general input data remain the same, are used. At the same time, they create a structure, which by its nature suitably represents the modelled stand. Some algorithms even account for the pattern and proportion of the species mixture (Pretzsch 1997).

Tools for forest **structure reproduction** represent a specific category derived from the tools used for structure reconstruction and structure generators, since they are used to generate an unknown forest structure outside inventory plots on the basis of the known structure at inventory plots (Pommerening 1999; Pommerening et al. 2000). It means that a part of a forest represents the actual situation at inventory plots, and a part is filled in by structure generators. Reproduction is used to create so-called representative stands.

Site generators are used to derive the data on site conditions, which are not available from usual information sources. They are used in models that require average or aggregate climatic characteristics as input for modelling the intensity of growth processes. An example of such situations is modelling of tree increments (effect) on the base of the value of a site variable (dose) and cumulating of effects caused by multiple site variables (Kahn 1994). Site generators derive required variables on the base of the commonly available data, e.g. geographical coordinates or a forest region, elevation, aspect and slope of the terrain, etc. Different approaches are used, e.g. climate regionalisation using geo-informatic procedures (Fabrika et al. 2005).

Weather generators are used primarily in process-based models that require information on weather characteristics for short time periods, e.g. hours or days. Due to frequent unavailability of such data, they are generated using models, which the average or aggregate meteorological data representing a longer period, usually a year or a growing season, distribute to individual months, days or hours. Algorithms are commonly based on statistical approaches. At present there are many models of this nature. As examples we can name WGEN (Richardson & Wright 1984), SIMMETEO (Geng et al. 1986, 1988), TAMSIM (McCaskill 1990), CLIMGEN (Clemence 1997), MET&ROLL (Dubrovský 1997), LARS-WG (Semenov et al. 1998), AAFC-WG (Hayhoe 2000), MARKSIM (Jones & Thornton 2000), RUNEOLE (Adelard et al. 2000), WM2 (Hansen & Mavromatis 2001) or CLIMA (Donatelli et al. 2009).

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Models of numerical weather prediction are used everywhere, where scenarios of temporal development of climatic characteristics are required for simulations of future forest production. They are mostly models of atmospheric physics that use quantitative methods for simulating interactions between atmosphere, oceans, earth's surface and ice. These models are very complex and demanding for computing power. Therefore, supercomputers or other technologies of high-performance computer processing of data are frequently used. In Europe, ALADIN (Huth et al. 2003) is a well-known and frequently used model.

3. Perspectives of forest models and visualisation

3.1. Vision on future development of forest modelling

The development of forest models is currently very significant. Among the many important perspectives and challenges of further development, the following can be mentioned:

a) **Hybridisation of models**. Specific model types are associated with specific applications. No model type is universal for all problems. Each one is suitable for a certain type of tasks. Therefore, the versatility of models is often addressed by the hybridisation of approaches (Kimmins et al. 2010), e.g. by a combination of an empirical concept with a process-based one. Model hybridisation extends the scale of model usage.

b) **Downscaling, upscaling, multiscaling.** Each model type is focused on a particular type of objects (Fig. 2). However, tasks to be solved often exceed the framework of one type of the modelled object. It ranges from the organ through the tree and population to the landscape. Therefore, it is necessary to choose a so-called core model from which more generalised objects are modelled by upscaling and more detailed objects by downscaling (Aertsen et al. 2012). This is a serial approach to forest modelling when the outputs of core models are used as inputs in subsequent models, namely forward sequence (upscale) or reverse sequence (downscale). It is also possible to use multiscaling parallel approaches, when multiple object types are modelled at the same time using multiple types of models and the resulting outputs are combined in the required way.

c) **Development of process-based models.** Climate change requires models that are more sensitive to environmental factors in planning. Process-based models are more suitable for these purposes than empirical models because they use causal relationships between environmental factors and growth instead of regression relationships. Hence, they can also capture growth responses that are beyond the growth reactions known from the present. Regression relationships are valid only for the population, from which the sample was taken and only for the period, in which the values of the environmental factors were valid. Outside these ranges, the prognoses do not have to capture the real behaviour of the forest since regression models extrapolate the performance beyond the data limits.

d) **Quantification of ecosystem services**. Forest policy changes because of pressures from society and thus the target ecosystem services are also changing. There are increasing demands to quantify ecosystem services using basic or auxiliary variables, resp. linking functions (Biber et al. 2015). This is a complex issue given that the assessment of some ecosystem services is very complex or based on subjective or aesthetic principles. Hence, their quantification does not always correlate with basic or auxiliary variables that are the output of the models.

e) **Open software solutions and shells.** A large number of prognostic tools nowadays exist. Therefore, efforts are made to unify the environment to enable the use of heterogeneous models or the integration of the program interface to connect various algorithms of models, so called shells. A good example is CAPSIS tool (Dufour-Kowalski et al. 2012).

f) **Interfaces to sophisticated data collection methods**. Many of the models, especially those that work with higher details such as organs or trees, require a large set of input data. Therefore, methodologies linked to forms of collecting detailed data, such as point clouds derived from terrestrial laser scanning (Liang et al. 2016) or close-range photogrammetry (Mikita et al. 2016; Mokroš et al. 2018a, b), have been developing over the last years.

g) **Application of precision forestry methods**. Recently, operational, tactical and strategic planning methods have been developing very intensively. They are closely connected with tools to predict forest development. As new inventory methods working with tree-level detail (parameters and positions) and prognostic tools with adequate modelling detail have become available, the so-called precision forestry method (Fox et al. 2008) has been implemented in the planning.

h) **Development and use of decision support systems (DSS).** The principles of flexibility and planning adaptability require prognoses for multiple scenarios of climate development, economic development, forest management variants, etc. Simulating all variants and/or scenarios produces extensive databases that need to be processed and evaluated. Decision support systems (Sodtke et al. 2004) are used to analyse the results of the prognoses. They are based on different procedures such as mathematical programming, knowledge-based and expert systems, neural networks, datamining methods, etc. Their goal is to

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select the most suitable forest management variant in relation to the chosen scenarios and a set of objectives (target ecosystem services). It is clear from the nature of the problem that these are multi-criteria forms of decision making.

3.2. Expected progress in forest visualisation

The need for communication with the public and easier interpretation of simulation results requires the development of forest visualisation tools. Several issues need to be addressed from this persepctive, such as linking forest landscape generators to forest inventory data and geographic information systems, use of high-quality 3D models for objects (organs, trees, plants, etc.), game engine integration, physical model implementation (shadows, wind movements, weather, etc.), the use of modern hardware tools to display virtual reality (HMD, CAVE). Such tools enable that the prognosis results are available in the form of a virtual forest or virtual forest landscape.

Immersion is a very important property of visualisation. Immersion can be achieved with specialised hardware. Some authors have tried to implement immersion in the easiest and cheapest way using the HMD devices, e.g. Oculus Rift (Oculus 2017). Although such a solution provides a fully immersive experience, is affordable and space-undemanding, it is limited to a single user. The possibilities of the cooperative mode with multiple users were resolved with the devices of the CAVE type (Cruz-Neira et al. 1992).

Many of the CAVE systems are prototypes that meet specific requirements. According to the visualisation purposes, they are built in various configurations of projection walls (DeFanti et al. 2011). They can either consist of one front, two side walls and a floor, as it was in the case of the first CAVE system (Cruz-Neira et al. 1993), or the user can be completely surrounded by the projection, as it is in e.g. 5-wall StarCAVE (DeFanti et al. 2009), or 6-wall CAVE systems such as Cornea (Cornea 2017), C–6 in Iowa (VRAC 2008), etc.

CAVE systems are based on the back-projection at the projection walls with the projectors, although more modern devices employing screens instead of projection walls are also built. Such a system was constructed by a team of EVL scientists and is known as CAVE2 (Febretti et al. 2013), which indirectly indicates the second generation of the systems. They also often exist in the form of mobile display panels consisting only of several screens such as NextCAVE (Merrill 2009). Using screens for the visualisation deals with the requirements on high resolution and contrast compared to systems based on projectors, but construction of such systems completely surrounding the user is still a major technological challenge (DeFanti et al. 2011). One problem is, for example, separation of the screens through their frames and a more difficult production of a stereoscopic image with regard to the number and configuration of displays.

Another important aspect of visualisation is the movement in virtual reality. The simplest approach is the movement with various control devices in user's hands. However, this is often not sufficient for a complex experience, especially in the case of the trainers working directly with man´s movement. This shortcoming was eliminated by the developers of the systems such as Virtusphere (Virtusphere 2017) or Cybersphere (Fernandes et al. 2003) that are based on the natural movement of the user inside the polycarbonate sphere which rolls over the system of bearings affixed to a firm base. This system is not compatible with the equipment of the CAVE type, because it is a different technological solution. The image is either projected into a helmet of the HMD type, or at the sphere itself with back-projection but without the stereoscopic character. The systems can be used by a single user only, because the movement of more persons in one sphere is problematic, if not dangerous. Developers of other devices, e.g. Virtuix Omni (Virtuix 2017) or Cyberith Virtualizer (Cyberith 2017), also deal with the possibilities to use the natural forms of movement. These are independent technological solutions that are based on the principle of user movement on a special pad. The pad is equipped with sensors that record movement and transform it into virtual reality. This fact opens possibilities of mutual integration of these devices with other systems such as the HMD or CAVE systems.

However, hardware is not the only thing that is important for the quality, interactivity and immensity of forest visualisation. Software solutions are also important. In the past, specialised programs using simple objects and support libraries (OpenGL, DirectX) and languages (VRML97, X3D) were frequently used, while today more complex Game Engines based environments (Unity 3D, Unreal Engine, CryEngine) are applied. These environments take full advantage of today's graphics cards and support physical processes (light propagation, shadow casting, wind movements, refraction of light on particles in the air, surface mirroring, light reflections from objects, gravity on objects, etc.). The future of visualisation lies in the massive deployment of Game Engines, their integration with specialised hardware (HMD, CAVE) and the transition from the visualisation of smaller forest areas to the visualisation of whole forest landscapes.

4. Conclusion

Forest models are based on a wide variety of different approaches that are used for their construction. This variety reflects the needs of the forestry community for specific parameters to be calculated. The number of specific tasks that need to be solved with forest models has increased since the beginning of model development. Frequently, the tasks are very complex and thus can only

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partially be solved by specific models. Hybridisation or scaling of forest models are possible approaches to solve this issue. Defined model classification and description helps users in fast orientation and selection of appropriate models for specific application. An overview of visualisation tools provides us with available possibilities to present complex forest ecosystems, and a wide variety of outputs from models in an easy and understandable way.

Acknowledgements

This study was supported by the Slovak Research and Development Agency under contracts APVV–0069–12, and APVV-15-0265, and by the Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic under contract KEGA 011TU Z-4/2019. KM was also supported by grant "EVA4.0", No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by OP RDEEVA4.0.

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Cent. Eur. For. J. 65 (2019) 166–179 sciendo DOI: 10.2478/forj-2019-0017

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Fir (*Abies* spp.) stand biomass additive model for Eurasia sensitive to winter temperature and annual precipitation

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Abstract

Climate change, especially modified courses of temperature and precipitation, has a significant impact on forest functioning and productivity. Moreover, some alterations in tree biomass allocation (e.g. root to shoot ratio, foliage to wood parts) might be expected in these changing ecological conditions. Therefore, we attempted to model fir stand biomass (t ha^{-1}) along the trans-Eurasian hydrothermal gradients using the data from 272 forest stands. The model outputs suggested that all biomass components, except for the crown mass, change in a common pattern, but in different ratios. Specifically, in the range of mean January temperature and precipitation of −30°C to +10°C and 300 to 900 mm, fir stand biomass increases with both increasing temperature and precipitation. Under an assumed increase of January temperature by 1°C, biomass of roots and of all components of the aboveground biomass of fir stands increased (under the assumption that the precipitation level did not change). Similarly, an assumed increase in precipitation by 100 mm resulted in the increased biomass of roots and of all aboveground components. We conclude that fir seems to be a perspective taxon from the point of its productive properties in the ongoing process of climate change.

Key words: fir forests; stand biomass; regression models; additive biomass equations; hydrothermal indices

Editor: Martin Lukac

1. Introduction

Since 1850, the amount of greenhouse gases in the atmosphere has doubled, threatening the planet with catastrophic climate change (Fatichi et al. 2019). At the UN climate summit in Paris in December 2015, 196 countries committed to reducing CO_2 emissions and preventing mean global temperature from rising by more than 2°C by the end of the century. Forest ecosystems, as sinks of atmospheric carbon, play an important role in this perspective. The ability of forests to sequester atmospheric carbon and to produce organic matter represents the basis of their functioning (Dylis 1978). The concentration of CO_2 in the atmosphere can be reduced by increasing carbon stock in the vegetative cover by effective forest management. On the other hand, climate change has a significant impact on vegetation productivity, which in turn affects cycling of organic matter and gas exchange in the biosphere (Golubyatnikov & Denisenko 2009).

Key data describing the quantitative characteristics of world forests are needed for a global quantitative description of natural and social phenomena (including biosphere functions of forest cover), the scientific community therefore needs to respond to the onset of the Big Data Era (Kudyba et al. 2014). In recent years, scientists from a number of countries have created unified global databases of empirical data and have derived general patterns describing fundamental functions of forest cover. To deepen our understanding of global forest ecosystems, the preference for large-scale synthesis of environmental data and modern digital learning methods is becoming increasingly apparent (Crowther et al. 2015; Poorter et al. 2015; Liang et al. 2016; Lockers et al. 2016; Jucker et al. 2017; Bohn & Huth 2017).

Temperature and precipitation are the key climatic factors that determine not only the radial growth of

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tree stems, but also forest stand productivity as a whole (DeLucia et al. 2000; Ni et al. 2001; Stegen et al. 2011; D'Aprile et al. 2015; Fang et al. 2016). Numerous studies of stochastic relationships of stand productivity with temperature and precipitation have been carried out at a regional level without accounting for stand age and morphology, and at a global level with or without taking species composition into account (Lieth 1974; Anderson et al. 2006; Keeling & Phillips 2007; Huston & Wolverton 2009). The analysis of the results from such studies revealed significant contradictions and uncertainties associated with the assessment of the dependence of these indices on temperature and precipitation using either empirical or functional models (Eggers et al. 2008; Shuman & Shugart 2009; Poudel et al. 2011; Han et al. 2018). Contradictory results were obtained even within the same region (Eggers et al. 2008; Shuman & Shugart 2009; Poudel et al. 2011; Han et al. 2018). Moreover, the influence of the climatic factors on biomass production of certain tree species (genera) along Trans-Eurasian climatic gradients of temperature and precipitation is still unknown, since the underlying information is fragmentary or contradictory (Wilmking et al. 2004; Stegen et al. 2011; Fu et al. 2017).

Fir (*Abies* spp.) is a genus comprising about 50 species of evergreen coniferous trees belonging to the *Pinaceae* family. They frequently occur in Eurasia, North and Central America, and North Africa, mainly in the mountainous regions. Under the Eurasian conditions, the most frequent Abies species are: *A. alba* Mill., *A. sibirica* L., *A. nephrolepis* Maxim., A. *nordmanniana* Spach., A. *spectabilis* (D. Don.) Mirb., and A. *sachalinensis* (F. Schmidt) Mast., A. veitchii Lindl., A. firma Sieb. et Zucc. In the European territory, *Abies alba* has been the most frequently studied species of this genus (e.g. Barbu & Barbu 2005; Savill et al. 2016). Recent research has shown that although *Abies alba* is much less significant economically than *Picea abies* L. Karst and *Pinus sylvestris* L. (both are most common coniferous trees), it might just be the species with the best future perspective under the ongoing climate change (Lindner et al. 2008). The latest work (Bosela et al. 2018) has shown that *A. alba* has a great productive potential, which has recently improved due to the reduction of acid deposition in Central Europe.

When constructing and using allometric models of tree biomass the principle of additivity need to be accounted for (Jacobs & Cunia 1980). Additivity of biomass components means that the resulting sum of biomass estimates of individual tree components (stems, branches, foliage, roots) obtained from component equations is equal to the value of the total biomass obtained from a general equation for the whole tree (Young et al. 1964). An analysis performed by Sanquetta et al. (2015) showed that additivity of biomass components is not ensured in 80% of derived models, mainly due to the complexity of statistical analyses and the inaccessibility of adequate modern software (Bi et al. 2004).

The first attempts to implement the principle of additivity were performed in the late 1960s and early 1970s on the examples of linear biomass models (Kurucz 1969; Kozak 1970). They were followed by the transition to additive systems of nonlinear equations, which are more suitable for accurate biomass quantification, but their computational algorithms are much more complex. One of recent developments is a two-step nonlinear seemingly unrelated regression (Parresol 2001; Dong et al. 2016). The statistical accuracy and, accordingly, the complexity of the calculation algorithms, was consistently increasing as such models were developed, and therefore modern software tools were required. All aforementioned additive systems of equations use an "aggregation" method based on the principle "from the particular (i.e. from component equations) to the general".

Recently, a disaggregation method of proportional weighing based on the principle "from general to particular" was proposed and developed as an alternative to the above-mentioned approach. It has been implemented in two versions: as two-step (Zheng et al. 2015) and three-step (Dong et al. 2015) additive systems of disaggregated equations. The first of them has been applied to aboveground biomass, while the second to total tree biomass, i.e. both aboveground and underground parts.

To date, the influence of climate change on biomass of tree species has not been studied by a systematic application of additive models in accordance to transcontinental hydrothermal gradients. Hence, the purpose of this study was to develop an additive model of biomass estimation of fir stands along the Trans-Eurasian gradients of mean January temperatures and precipitation. The Eurasian database of biomass in trees and individual tree components compiled by Usoltsev (see works: Usoltsev 2010, 2013 for more details) makes it possible to perform an analysis of biological productivity (eventually for both biomass and carbon) at a trans-continental level. The variation range of mean temperatures and precipitation in Eurasia is large and covers a spectrum of natural ecosystems. We hypothesise that the biomass structure of fir stands may be described by an additive system of equations based on two hydrothermal indices – mean January temperature and mean annual precipitation all over Eurasia (i.e. under a wide range of variation of hydrothermal indices). We decided to use the mean January temperature, because warming is most pronounced in the cold half of the year (Golubyatnikov & Denisenko 2009; Laing & Binyamin 2013; Felton et al. 2016) and also because winter temperature was found decisive for fir growth (Schwarz 1899; Bijak 2010; Toromani & Bojaxhi 2010).

2. Material and methods

A database describing biomass of forest-forming species of Eurasia (Usoltsev 2010, 2013), consisting of

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data about the whole tree biomass and individual tree components published by a large number of authors, was used in this study. From this database, 272 sampling sites with the biomass data of fir forest stands were selected (Table 1, Fig. 1 and Fig. 2). At each site, several sample trees were selected for biomass sampling of individual tree components. In general, 5 to 10 trees were sampled from each site with the exception of 23 sites established in the Carpathians (Lakida & Domashovets 2009), from which only 3 – 4 trees per site were harvested and processed. From the sample trees, biomass samples were taken from every tree component to determine the dry matter content, and tissue density for wood and bark of stems. Individual biomass components are not equally presented in the database since not all components were determined at each site. Hence, the mass of stems above bark and needles was quantified for all 272 sites, while the mass of branches, stem bark and roots only for 255, 151, and 66 sites, respectively.

Sampling procedures for estimating biomass of tree components differed between the studies, since they were performed by representatives of different scientific fields in forestry. However, these small methodological differences do not play the determining role in the level of accuracy of biomass estimates, because there is only one definite variant of biomass component structure corresponding to a given morphological structure of a tree stand (Usoltsev 2007).

The matrix of biomass data representing individual components and forest stand characteristics was assessed against the main driver variables of mean January temperature (Fig. 1) and precipitation (Fig. 2) taken from World Weather Maps (2007). It is known that the effectiveness of modelling of biological communities (of which a forest is the most complex one) depends on the implementation level of a meaningful analysis of the initial data, i.e. on a studied level of the structure of the impact of factors on an object, changing in time and space. To ensure the maximum stability of the model, each of the selected independent variables should be presented in the maximum range of its variation (Usoltsev 2004). In our case, mean January temperatures range from −40°C in the forest-tundra of the North–Eastern Siberia to +15°C in the subtropics of Nepal, and mean annual precipitation from 190 mm in the permafrost regions of North-Eastern Siberia and the steppe zone of Eurasia to 1,140 mm in the territory of Nepal.

The matrix containing biomass data, stand variables, and climate characteristics was used as a source of data for the subsequent regression analysis to derive equations for estimation of total biomass and its components. Forest biomass was described using a power function, which belongs to the most widely used functions for such purposes (Picard et al. 2012). When choosing independent variables of the regression model, we adhered to the concept that there is only one definite variant of stand biomass structure corresponding to a given set of taxonometric parameters describing a forest stand (Usoltsev, 2007). The initial structure of the model included the main mass-forming factors of stands – age, stem volume, tree density, mean diameter and mean height. Mean diameter correlated with tree density and mean height correlated with age. Hence, they were excluded in the process of the regression analysis. The synergism (lnA)·(lnN) was introduced in the model to account for the decrease in tree density with age and its effect on the

Table 1. List of 272 sites with biomass data representing *Abies* spp. used for the construction of additive models.

Country	Species of *Abies*: English name	Species of *Abies*: Latin name	Number of sampling sites	Range of: Age [years]	Range of: Tree density [pcs ha^{-1}]	Range of: Stand volume [m^3 ha^{-1}]	Range of: Above ground biomass [t ha^{-1}]	Range of: Root biomass [t ha^{-1}]	References
Italy	Silver fir	*A. alba* Mill.	16	20–95	512–2548	173–1095	86–467	Not available	Cantiani 1974; Hellrigl 1974
Romania	Silver fir	*A. alba* Mill.	1	110	485	1000	470	Not available	DeAngelis 1981
Czech Republic	Silver fir	*A. alba* Mill.	1	51	1667	216	119	15	Vyskot 1972, 1973
Ukraine	Silver fir	*A. alba* Mill.	46	6–99	223–7400	12–770	14–326	6–60	Odinak et al. 1986; Lakida and Domashovets 2009
Russia	Siberian fir	*A. sibirica* L.	142	20–200	165–54080	30–540	17–212	8–48	Khanbekov 1972; Krauklis et al. 1975; Kuzikov 1979; Onuchin & Borisov 1983; Mitrofanov et al. 1986; Usoltsev & Antropov, 2001; Andriyanova 2001; Koshurnikova 2007; Usoltsev et al. 2012
	Khingam fir	*A. nephrolepis* Maxim.	11	41–192	587–5125	68–383	40–189	38–51	Dyukarev & Rozenberg 1975; Opritova et al. 1982
	Nordmann fir	*A. nordmanniana* Spach.	5	160–283	332–544	601–1294	327–598	69–101	Orlov 1951; Veselov 1973
Nepal	Himalayan fir	A. spectabilis (D.Don) Mirb.	6	100	275–1450	336–758	158–417	38–102	Yoda 1967, 1968
Japan	Todo-fir	*A. sachalinensis* (F.Schmidt) Mast.	7	8–35	1178–2870	1–321	1–196	Not available	Yamamoto & Sanada 1970; Satoo 1973; Ueda 1974;
	Veitch's fir	*A. veitchii* Lindl.	26	13–126	1204–19500	114–568	68–257	4–62	Oshima et al. 1958; Kimura 1963; Oohata & Oniishi 1974; Tadaki et al. 1977
	Momi-fir	*A. firma* Sieb. et Zucc.	11	120	353–1250	157–930	90–502	145	Furuno & Kawanabe 1967; Ando et al. 1977; Furuno et al. 1979

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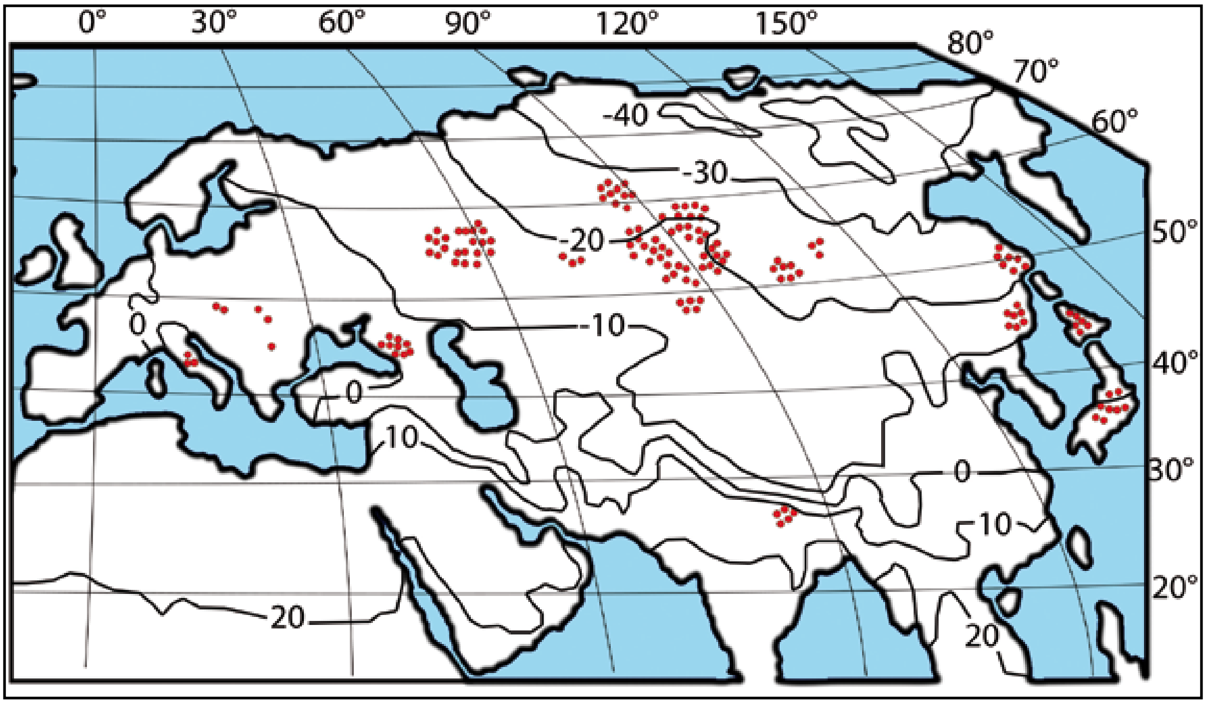

Fig. 1. Location of 272 *Abies* spp. for biomass sampling sites (in most cases biomass was determined specifically for each tree component; i.e. needles, branches, stem bark, stem wood, and roots) with regard to the mean January temperature [°C] (source: World Weather Maps 2007; see also https://store.mapsofworld.com/image/cache/data/map_2014/currents-and-temperature-jan-enlarge-900x700.jpg).

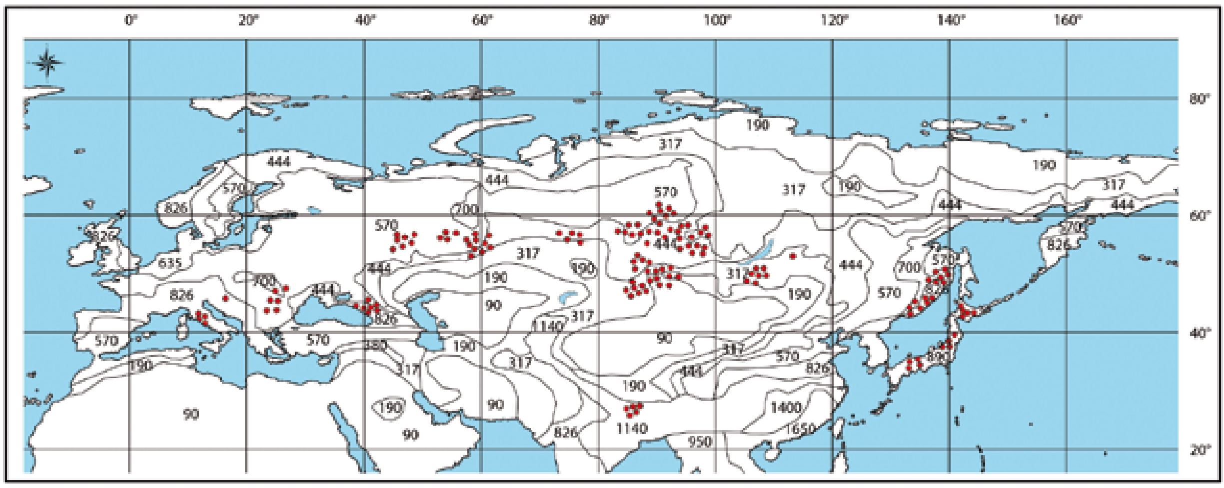

Fig. 2. Location of 272 *Abies* spp. biomass sampling sites (in most cases biomass was determined specifically for each tree component; i.e. needles, branches, stem bark, stem wood, and roots) with regard to the mean annual precipitation [mm] (source: World Weather Maps 2007; see also http://www.mapmost.com/world-precipitation-map/free-world-precipitation-map/).

stand biomass. In addition, the climate characteristics, namely mean January temperature and annual precipitation total, were included in the model to account for the impact of environmental conditions. The final model included only those variables that were found significant for all biomass components. Hence, the general regression equation was:

$$\ln P_i = a_{0i} + a_{1i}(\ln A) + a_{2i}(\ln V) + a_{3i}(\ln A)\cdot(\ln N)\; a_{4i}[\ln(Tm+40)] + a_{5i}(\ln PRm) + a_{6i}[\ln(Tm+40)]\cdot(\ln PRm) \qquad [1]$$

where P_i is biomass of i^{th} component, t per ha; *A* is stand age, yrs; *V* is stand stem volume above bark, m^3 per ha; *N* is tree number, 1000 per ha; *i* is index of biomass components as follows: total (*t*), aboveground (*a*), roots (*r*), crown (*c*), stem above bark (*s*), foliage (*f*), branches (*b*), stem wood (*w*), and stem bark (*bk*); *PRm* is mean annual precipitation total, mm; *Tm* is mean January temperature, °C. Since the mean January temperature at the northern limit of Eurasia is negative (Fig. 2), the corresponding independent variable was increased by 40 (*Tm*+40) to enable a logarithmic transformation according to Baskerville (1972). The problem of transforming the model (1) into a tabular form

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is that we can specify only stand age, temperature, and precipitation, while stem volume and tree density can be obtained by a system of auxiliary recursive equations having the general form:

$$N = f\,[A, (Tm+40), PRm] \qquad [2]$$

$$V = f\,[A, N, (Tm+40), PRm] \qquad [3]$$

The regression coefficients of multiple regression equations [1], [2], and [3] were calculated using the Statgraphics software (see http://www.statgraphics.com/ for more information).

First, an initial equation for the estimation of the total tree biomass was derived. Then, a three-step additive disaggregation system of equations was applied (e.g. Dong et al. 2015; Zheng et al. 2015). Hence, the total biomass estimated from the initial equation was divided into its constituent parts according to the scheme presented in Fig. 3. In the first step, the total tree biomass was divided into roots and the aboveground part in accordance with their shares in the total biomass represented by the corresponding component equations (step 1). Afterwards, the resulting aboveground biomass was divided in the same way into the crown and the stem above bark (step 2). Finally, the crown biomass was divided into foliage and branches (step 3a), and stem biomass into wood and bark (step 3b) (Fig. 3). Such an algorithm enables the simulation of a component structure of forest stand biomass despite different representation of the components in the total biomass, because their relative proportions are used as a basis instead of absolute values, which minimises the bias of estimates.

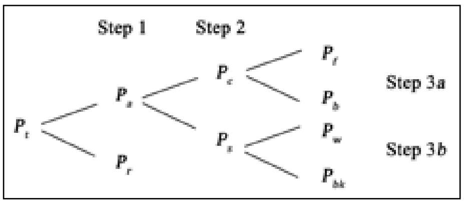

Fig. 3. The pattern of the disaggregating three-step proportional weighting additive model. Designation: *Pt, Pr, Pa, Pc, Ps, Pf, Pb, Pw* and *Pbk* represent stand biomass in t per ha as follows: total, underground (roots), aboveground, crown (foliage and branches), stems above bark (wood and bark), foliage, branches, stem wood and stem bark, respectively.

3. Results

The initial equations after the correction for logarithmic transformation by Baskerville (1972) and anti-log transforming are characterised by the significance level of at most 0.05 (Table 2). The equations represent the biomass data included in the above mentioned database. These equations were modified to the additive form according to the algorithm presented in Fig. 3. As a result, we obtained the final form of the transcontinental additive model of component composition of fir biomass, shown in Table 3.

The comparison of observed biomass with the predicted values using the initial (Table 2) and additive (Table 3) equations confirmed the adequacy of the

Table 2. Characteristics of initial models (1) after their anti-log transformation. Designation: *A* is stand age, yrs; *V* is stand stem volume above bark, m^3 per ha; *N* is tree number, 1000 per ha; *PRm* is mean annual precipitation total, mm; *Tm* is mean January temperature, °C, P is stand biomass, t per ha, in biomass components as follows: total (*t*), aboveground (*a*), roots (*r*), crown (*c*), stem above bark (*s*), foliage (*f*), branches (*b*), stem wood (*w*), and stem bark (*bk*). The abbreviation *adjR²* is a coefficient of determination adjusted for the number of parameters; *SE* – equation standard error.

Biomass component	Initial model characteristics				
P_t	2.79E-02	$A^{0.1288}$	$V^{0.7793}$	$A^{0.0114\ln(N)}$	$(Tm+40)^{0.5654}$
Step 1					
P_a	2.66E+03	$A^{0.0762}$	$V^{0.8415}$	$A^{0.0092\ln(N)}$	$(Tm+40)^{-2.8453}$
P_r	1.98E-01	$A^{0.1440}$	$V^{0.7773}$	$A^{0.0289\ln(N)}$	$(Tm+40)^{-1.0832}$
Step 2					
P_c	1.21E+06	$A^{0.0042}$	$V^{0.5849}$	$A^{0.0188\ln(N)}$	$(Tm+40)^{-4.8792}$
P_s	1.19E+02	$A^{0.1163}$	$V^{0.9601}$	$A^{0.0060\ln(N)}$	$(Tm+40)^{-2.1101}$
Step 3a					
P_f	1.04E-06	$A^{-0.1735}$	$V^{0.5351}$	$A^{0.0214\ln(N)}$	$(Tm+40)^{3.3463}$
P_b	2.77E+09	$A^{0.1344}$	$V^{0.6633}$	$A^{0.0141\ln(N)}$	$(Tm+40)^{-7.5829}$
Step 3b					
P_w	4.14E-10	$A^{0.2061}$	$V^{0.9849}$	$A^{0.0225\ln(N)}$	$(Tm+40)^{6.0684}$
P_{bk}	3.40E+07	$A^{0.2179}$	$V^{0.7755}$	$A^{0.0345\ln(N)}$	$(Tm+40)^{-6.0017}$

Biomass components	Initial model characteristics		adjR²*	SE*
P_t	$PRm^{0.4209}$	$(Tm+40)^{-0.0396\ln(PRm)}$	0.961	1.16
Step 1				
P_a	$PRm^{-1.3083}$	$(Tm+40)^{0.4588\ln(PRm)}$	0.971	1.15
P_r	$PRm^{-0.0796}$	$(Tm+40)^{0.1917\ln(PRm)}$	0.868	1.34
Step 2				
P_c	$PRm^{-2.1828}$	$(Tm+40)^{0.7610\ln(PRm)}$	0.805	1.32
P_s	$PRm^{-0.9855}$	$(Tm+40)^{0.3414\ln(PRm)}$	0.983	1.13
Step 3a				
P_f	$PRm^{2.1635}$	$(Tm+40)^{-0.5177\ln(PRm)}$	0.628	1.47
P_b	$PRm^{-3.5753}$	$(Tm+40)^{1.1677\ln(PRm)}$	0.804	1.40
Step 3b				
P_w	$PRm^{2.8542}$	$(Tm+40)^{-0.8792\ln(PRm)}$	0.978	1.13
P_{bk}	$PRm^{-3.3007}$	$(Tm+40)^{0.9810\ln(PRm)}$	0.928	1.20

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derived models, since they usually explained more than 50% of variability in biomass depending on the biomass component (Fig. 4). The variability of aboveground and stem biomass was captured well, as our equations explained more than 90% of observed variance (Fig. 4). High correlation between predicted and observed biomass was also observed for stem wood (R^2 of around 0.8), followed by roots, branches, and crown (R^2 of around 0.7). The model explained the least variability in the biomass of foliage and stem bark (Fig. 4).

The equations [2] and [3] derived from the data on fir stands were significant at a level of 0.05 and explained 68% and 61% of variability of number of trees and stand volume per ha, respectively (Table 4). As Fig. 5 shows, the biomass of all components in 100-year-old fir stands grows as mean annual precipitation total and mean January temperature increase.

Under an assumed increase in temperature by 1°C, the model results showed that more biomass was accumulated in 100-year-old fir stands regardless of precipitation conditions in comparison to current temperature conditions (Fig. 6). Similarly, an increase in precipitation by 100 mm resulted in the increase in biomass of fir stands under all temperature and precipitation combinations present in this study of Eurasia (Fig. 7). The exceptions were the patterns for the foliage and branches, for which a slight decrease of their biomass was estimated in warm climatic zones (*Tm* = 10°C, Fig. 7) regardless of the existing level of precipitation.

4. Discussion

Our modelling suggested that biomass of all fir components grows as precipitation total increases from 300 to 900 mm, as well as due to the increase in the mean January temperature from −30°C to +10°C (Fig. 5). The finding is consistent with the increase in relative radial increment of boreal forests in Canada if both mean annual temperature and annual precipitation increase (Miao & Li 2011). However, this trend does not correspond to the results obtained using similar models for biomass quantification in two-needled pine forests of Eurasia (Usoltsev et al. 2019b). The pine models manifested different trends, since in cold zones (*Tm* = −20°C) precipitation increase leads to a decrease of biomass, while in warm zones (*Tm* = 10°C) to their increase, with the exception of root biomass. Correspondingly, temperature increase in wet areas (*PRm* = 900 mm) causes an increase of biomass in two-needled pine forests, while in dry areas (*PRm* = 300 mm) it causes their decrease, with the exception of roots. Derived additive models of fir stand biomass allow us to determine quantitative changes in the biomass structure due to the climate change, in particular, the mean January temperature and mean annual precipitation.

The change in the biomass structure is associated with the changes of these two climatic parameters. For example, if the mean January temperature in the central part of European Russia, characterised by the mean January temperature equal to −10°C and the mean annual precipitation equal to 400 mm (Fig. 1 and Fig. 2) is increased by 1°C, the model suggests that the biomass of all compo-

Table 3. Final three-step additive model of *Abies* forest biomass derived for Eurasia. Designation: *A* is stand age, yrs; *V* is stand stem volume above bark, m^3 per ha; *N* is tree number, 1000 per ha; *PRm* is mean annual precipitation total, mm; *Tm* is mean January temperature, °C, *P* is stand biomass, *t* per ha, in biomass components as follows: total (*t*), aboveground (*a*), roots (*r*), crown (*c*), stem above bark (*s*), foliage (*f*), branches (*b*), stem wood (*w*), and stem bark (*bk*).

	Model
	$Pt = 2.79E\text{-}02\, A^{0.1288} V^{0.7793} A^{0.0114 \ln(N)} (Tm+40)^{0.5654} PRm^{0.4209} (Tm+40)^{-0.0396 \ln(PRm)}$
Step 1	$Pa = \frac{1}{1+7.46E\text{-}05\, A^{0.0678} V^{-0.0642} A^{0.0197 \ln(N)} (Tm+40)^{1.7621} PRm^{1.2287} (Tm+40)^{-0.2671 \ln(PRm)}} \times Pt$
	$Pr = \frac{1}{1+1.34E{+}04\, A^{-0.0678} V^{0.0642} A^{-0.0197 \ln(N)} (Tm+40)^{-1.7621} PRm^{-1.2287} (Tm+40)^{0.2671 \ln(PRm)}} \times Pt$
Step 2	$Pc = \frac{1}{1+9.87E\text{-}05\, A^{0.1122} V^{0.3752} A^{-0.0128 \ln(N)} (Tm+40)^{2.7691} PRm^{1.1973} (Tm+40)^{-0.4196 \ln(PRm)}} \times Pa$
	$Ps = \frac{1}{1+1.01E{+}04\, A^{-0.1122} V^{-0.3752} A^{0.0128 \ln(N)} (Tm+40)^{-2.7691} PRm^{-1.1973} (Tm+40)^{0.4196 \ln(PRm)}} \times Pa$
Step 3a	$Pf = \frac{1}{1+2.66E{+}15\, A^{0.3079} V^{0.1283} A^{-0.0073 \ln(N)} (Tm+40)^{-10.9291} PRm^{-5.7388} (Tm+40)^{1.6854 \ln(PRm)}} \times Pc$
	$Pb = \frac{1}{1+3.77E\text{-}16\, A^{-0.3079} V^{-0.1283} A^{0.0073 \ln(N)} (Tm+40)^{10.9291} PRm^{5.7388} (Tm+40)^{-1.6854 \ln(PRm)}} \times Pc$
Step 3b	$Pw = \frac{1}{1+8.23E{+}16\, A^{0.0118} V^{-0.2094} A^{0.0120 \ln(N)} (Tm+40)^{-12.0700} PRm^{-6.1548} (Tm+40)^{1.8602 \ln(PRm)}} \times Ps$
	$Pbk = \frac{1}{1+1.22E\text{-}17\, A^{-0.0118} V^{0.2094} A^{-0.0120 \ln(N)} (Tm+40)^{12.0700} PRm^{6.1548} (Tm+40)^{-1.8602 \ln(PRm)}} \times Ps$

Table 4. Characteristics of the recursive system of auxiliary equations for fir stand characteristics.

Stand characteristics	Equation				
Tree number per ha	1.05E+33	$A^{-1.1176}$	exp[9.5436 (1/A)]	—	$(Tm+40)^{-25.1111}$
Stand stem volume above bark	6.91E-05	$A^{0.7152}$	$N^{-0.4815}$	$A^{0.0911 \ln(N)}$	$(Tm+40)^{2.6481}$
Stand characteristics	The auxiliary equations characteristics			$adjR^2$	SE
Tree number per ha	$PRm^{-9.9710}$		$(Tm+40)^{3.5812 \ln(PRm)}$	0.681	2.19
Stand stem volume above bark	$PRm^{1.5702}$		$(Tm+40)^{-0.3094 \ln(PRm)}$	0.613	1.76

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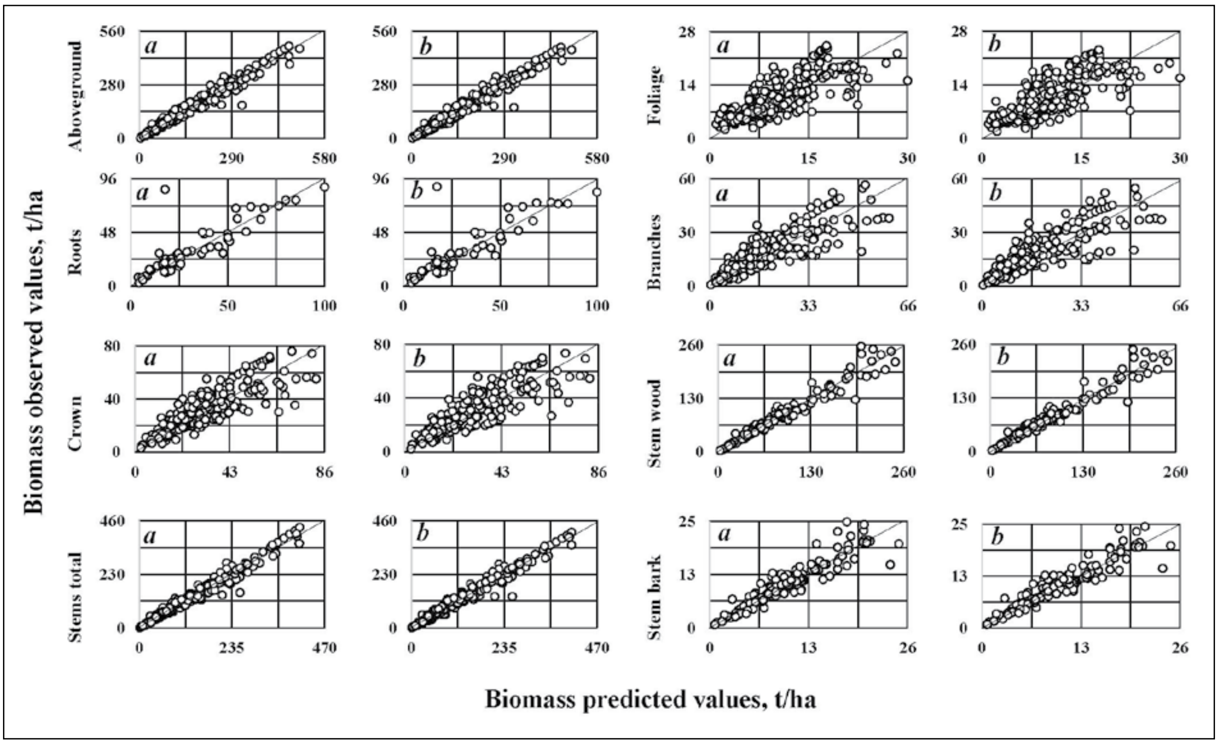

Fig. 4. Observed stand fir biomass plotted against predicted biomass obtained by calculating the initial (a) and additive (b) models.

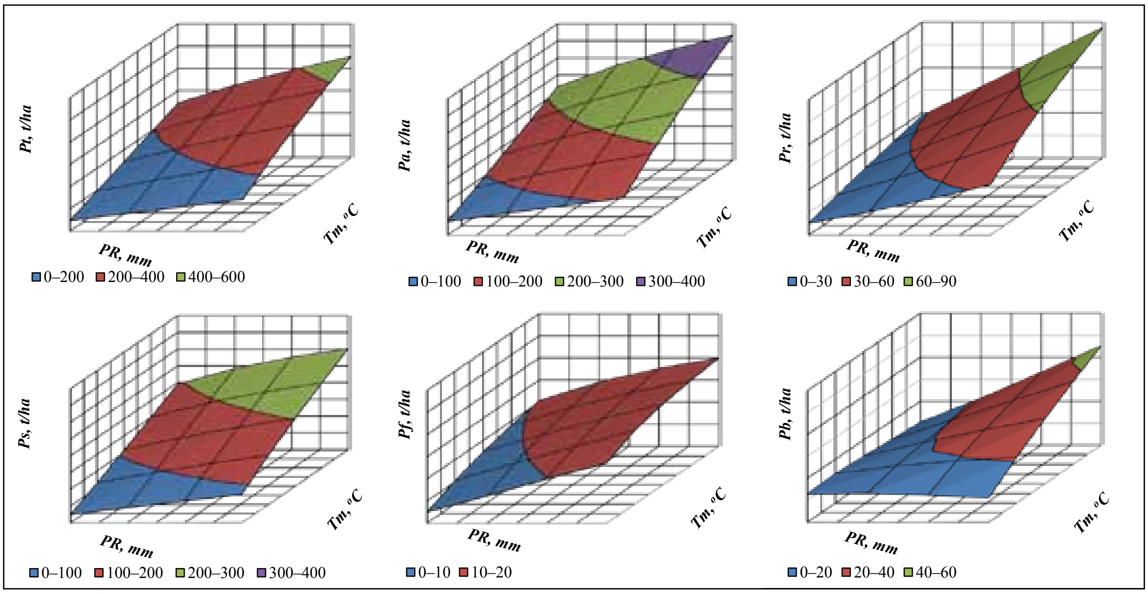

Fig. 5. The dependence of fir stand biomass upon mean January temperature (*Tm*) and annual precipitation (*PRm*) at the stand age of 100 years. Designation: *Pt, Ps, Pa, Pf, Pr,* and *Pb* – total biomass, biomass in stems, aboveground, foliage, roots, and branches, *t* per ha, respectively.

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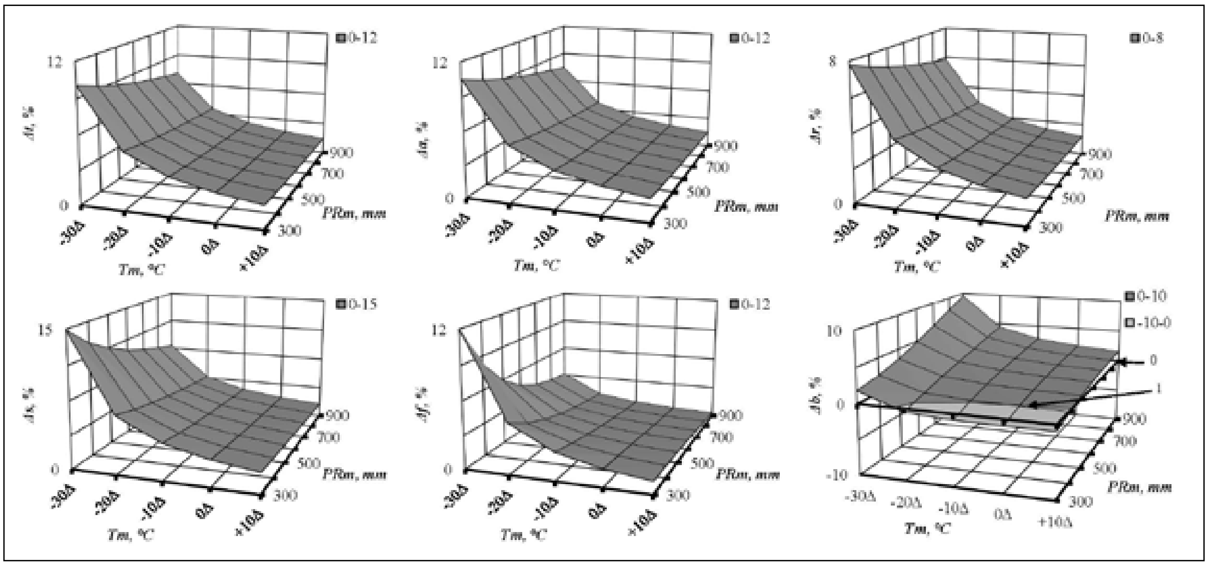

Fig. 6. Simulated changes in fir stand biomass due to the assumed temperature increase of 1°C based on the derived model (for the stands aged 100 years). *Tm* – mean January temperature, °C; *PRm* – mean annual precipitation, mm. Temperature values on *X* axis designated as −30Δ...+10Δ represent the mean January temperature increased by 1°C. The relative changes in individual biomass components (%) are marked as follows: total *ΔPt*, aboveground *ΔPa*, roots *ΔPr*, stems *ΔPs*, foliage *ΔPf* and branches *ΔPb*. The value 0 represents the plane corresponding to zero change of biomass at the expected temperature increase by 1°C; the value 1 represents the border between positive and negative changes in biomass (Δ,%) at the expected temperature increase by 1°C.

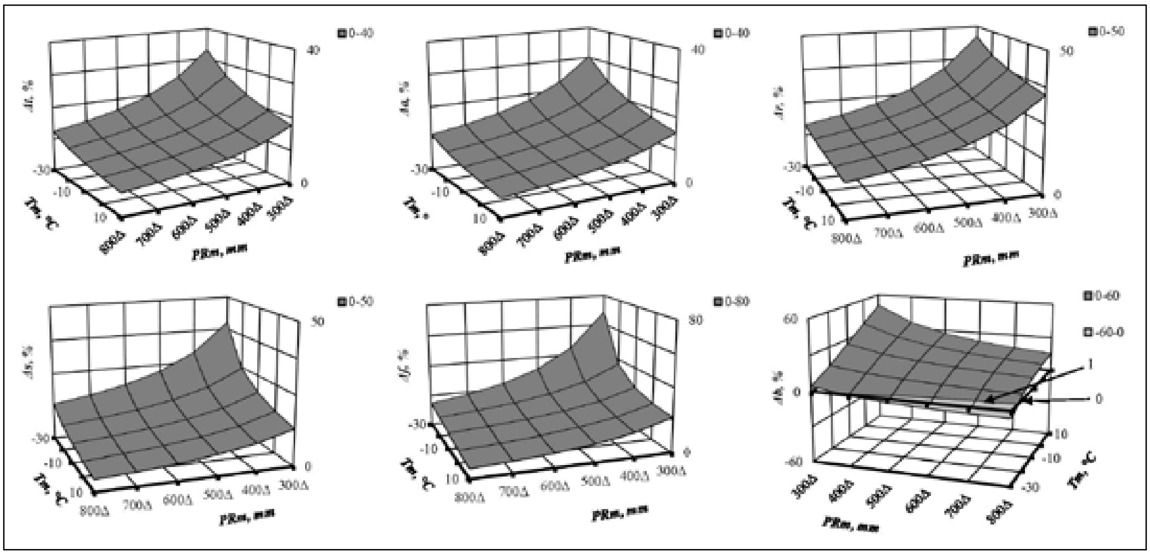

Fig. 7. Simulated changes in fir stand biomass due to the assumed precipitation increase of 100 mm (for the stands aged 100 years). *Tm* – mean January temperature, °C; *PRm* – mean annual precipitation, mm. Precipitation values on *X* axis designated as 300Δ...800Δ represent the annual precipitation total increased by 100 mm. The relative changes in individual biomass components (%) are marked as follows: total *ΔPt*, aboveground *ΔPa*, roots *ΔPr*, stems *ΔPs*, foliage *ΔPf* and branches *ΔPb*. The value 0 represents the plane corresponding to zero change of biomass at the expected temperature increase by 1°C; the value 1 represents the border between positive and negative changes in biomass (Δ,%) at the expected temperature increase by 1°C.

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nents in a 100-year-old stand would increase by 3.9, 3.8, 4.6, 3.8, 4.6, and 3.5 % in the case of total biomass, aboveground, roots, stems, foliage, and branches, respectively. Similarly, the increase in precipitation by 100 mm in the same region while keeping mean January temperature constant caused an increase in the total biomass, aboveground, roots, stems, foliage and branches by 12.5, 11.9, 15.3, 12.7, 1.4 and 1.9%, respectively. Our results show that both temperature and precipitation increases result in positive trends of biomass accumulation (Fig. 5). The exception is the foliage biomass, which in the warm zone (Tm = +10°C) decreases with increasing precipitation during the transition from the regions of insufficient moisture (PRm = 300 mm) to the regions of increased moisture (PRm = 900 mm).

Here, we would like to point out that not only total quantity of forest stand biomass but also its allocation to individual tree components is important from carbon sequestration point of view. For instance, a ratio between foliage, i.e. a component with fast carbon turnover, and woody parts, i.e. long-run carbon turnover, determines the rate of carbon cycling via tree biomass (e.g. Šebeň et al. 2017). Moreover, the root to shoot ratio describes carbon proportion situated above ground and in the soil. Those two different environments represent contrasting conditions for wood decomposition and carbon emission after tree perishes (e.g. Laiho & Prescott 2004).

It is generally known that the efficiency of environmental object modelling depends on the level of implementation of a meaningful analysis of empirical data, i.e. on the studied level of impact factors changing in time and space. In relation to a single factor, this principle means identifying the most informative (active) range of its effects (Liepa 1980) in order to identify the optimal range within which the selected factor, ambiguous in its informativeness, would explain the largest proportion of variability of the resulting variable. Our study uses the winter temperature index as the most sensitive to climate change, and one can draw an analogy with a similar process at a global level: the temperature at the Earth poles increases at an accelerated rate compared to the mainland (Henderson 2006). In the future, the impact of temperatures representing different parts of the year should be tested and the most significant period should be used in the models.

Presented approach of biomass calculation ensures that the sum of component biomass amounts obtained from component equations is equal to the value of the total biomass calculated with the general equation. Two algorithms have been proposed for this purpose: (1) an "aggregation" method based on the principle "from the particular (i.e. from component equations) to the general" (Parresol 2001), and (2) a "disaggregation" method of proportional weighing based on the principle "from general to particular" (Dong et al. 2015). When comparing aggregation and disaggregation methods using the data from 122 sample trees, Dong et al. (2015) concluded that although the results obtained by the two methods were similar, the second one led to a smaller standard error of regression coefficients. An advantage of our chosen disaggregated structure of the model is that it can be used for global or transcontinental modelling, because it uses climate variables as independent input, which cannot be included in the "aggregated" model (Parresol 2001). Another possible approach is to construct a system of regional equations and use dummy variables that specify particular ecoregions (Usoltsev et al. 2019a).

In order to understand possible impacts of climate change on forest biological productivity and to obtain sufficiently adequate simulation results of this relationship, it is necessary to provide empirical data on productivity and climate variables in the widest possible range of their variation, i.e. at global or continental levels. In a recent work (Zeller et al. 2018), geographical coordinates of sample plots, as well as annual precipitation and temperature were included in the model of forest productivity for the territories of Germany and the United States along with main defining independent variables. We contend that the evidence of the authors is contradictory because: (1) climate variables are correlated with geographical coordinates of sample plots in this model, and (2) the ranges of variability of climate variables within a country were too small to obtain stable patterns. To avoid such uncertain results, a transcontinental level of analysis was chosen in our study, and geographical coordinates were not included among independent variables.

The question may arise why modelling was performed at the level of *Abies* genus, and not for individual fir species. In the world affected by climate change, large-scale analyses are needed as they can provide us with general trends. The spatial distribution of individual *Abies species* in Eurasia is rather scattered and complementary (Savill et al. 2016), which does not allow for a large-scale analysis of individual species based on the available empirical data. In plant horology, this distribution is known as species substitution, or replacing of species, which occurs in the cases of paleo-geographically protracted dissociation of once continuous plant habitat (Hultén 1937; Tolmachev 1962) or due to the climatologically caused morphogenesis (Chernyshev 1974). A disadvantage of the database used in this study is the uneven spatial distribution of sampling sites over Eurasia (Fig. 2) resulting in different representation of individual ecoregions. Since in the regression analysis of biomass data we used the least squares method, estimates of biomass in ecoregions with a minimum number of sampling sites (Romania and the Czech Republic) may be biased due to the greater "information weight" of ecoregions with the largest numbers of sampling sites (Central Siberia and China). Methodological uncertainties causing biases in biomass amounts in individual tree parts may also affect the accuracy of the estimates. This applies primarily to the underground biomass. The analysis of the world data of underground tree biomass has showed that due to the

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imperfection of methods to estimate fine root biomass, the total underground biomass of stands may be underestimated two to five times (Usoltsev 2018).

As is usually the case, the solution of each new problem and the corresponding removal of the associated uncertainty generates several new ones. In our case, two main uncertainties have arisen:

1) The patterns of biomass amount change under assumed changed climatic conditions (Fig. 6 and Fig. 7) are hypothetical. They reflect long-term adaptive responses of forest stands to regional climatic conditions and do not take into account rapid trends of current environmental changes, which place serious constraints on the ability of forests to adapt to new climatic conditions (Alcamo et al. 2007).

2) The presented patterns are related to fir forests, which are either pure or with a slight admixture of other tree species. However, fir usually grows in mixed stands (Bosela et al. 2018). There is a body of evidence that mixed stands are more resistant to stress caused by abiotic factors and are more productive than pure stands (Liang et al. 2016). However, a recent study of net primary production (NPP) of aboveground biomass from forests in Spain and Canada over a wide range of biodiversity index values as well as of mean temperature and moisture conditions (Paquette et al. 2018) led to a paradoxical conclusion. The authors found that in pure forest stands (low value of biodiversity index), NPP reacts to temperature rise of 1 – 2°C in different climatic zones in different ways: it grows in temperate forests, remains stable in boreal forests and declines in the Mediterranean forests. However, as the biodiversity index increases, these trends gradually transform into a unified negative trend, common for all zones (Paquette et al. 2018). This result indicates that the revealed trajectories of changes in biomass and NPP of pure (or almost pure) forest communities may not hold under the conditions of variable climate: in forests with an increased biodiversity index, the patterns can be significantly modified and even reversed.

Taking into account the stated methodological and conceptual uncertainties, the results presented in this study should be considered as preliminary ones. They can be modified if the biomass database will be enlarged by additional data, mainly site-specific and stand-specific characteristics. Moreover, further inherent phenomena of climate change (especially CO_2 concentration in the atmosphere) could be potentially included in future models if the corresponding data were available.

5. Conclusion

This paper presents a model for calculating stand biomass of fir species along the trans-Eurasian hydrothermal gradient. The model was derived from the biomass data of nearly 300 fir stands and climate data. We revealed that all biomass components of examined stands changed in the same direction: fir stand biomass increased with the increasing precipitation within the evaluated range from 300 to 900 mm per year, as well as due to the increase in the mean January temperature from −30°C to +10°C regardless of the precipitation level. A modelled increase of January temperature by 1°C, or of precipitation by 100 mm, caused an increase in biomass of all components of fir stands. Our results indicate that fir would not suffer from the projected climate change. However, from the long-term perspective, climate change might bring even more drastic modification of winter temperature and annual sum of precipitation than was considered here. Therefore, our outputs represent a reasonable an example of model sensitivity to changing climatic conditions. The development of such models for the main forest-forming species of Eurasia allow predicting changes in the productivity of the forest cover of Eurasia in relation to climate change.

Acknowledgements

This paper was prepared within the programs of the current scientific research of the Ural Forest Engineering University and Botanical Garden of the Ural Branch of Russian Academy of Sciences. This work was supported by grant "EVA4.0", No. CZ. 02.1.01/0.0/0.0/16_019/0000803 financed by OP RDE, by the Slovak Research and Development Agency under contracts No. APVV-15-0265, APVV-16-0325, APVV-18-0086 and the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic under contracts No. VEGA 1/0367/16.

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Cent. Eur. For. J. 65 (2019) 180–190 sciendo DOI: 10.2478/forj-2019-0023

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Changes in growth caused by climate change and other limiting factors in time affect the optimal equilibrium of close-to-nature forest management

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Abstract

Historical radial increment data based on tree ring analyses from the close-to-nature experimental forest management unit Smolnícka Osada in Central Slovakia were used for retrospective modelling of changes in forest dynamics to estimate the sensitivity of management planning goals under climate change. Four example years representing historical periods with typically different species-specific patterns of radial increment in mixed beech-fir-spruce forest (1910, 1950, 1980, and 2014) served as virtual starting points for the modelling. An advanced density-dependent matrix transition model was utilised for modelling stand dynamics. An integrated tool for nonlinear financial optimisation searched for an optimal management equilibrium. In addition to transition probabilities adjusted from increment data, some assumptions for changes in ingrowth and mortality related to the increment, as well as a case study concerning the reduced ingrowth changed by game browsing intensity, were tested for modelling more realistic historical ecological conditions. The sensitivity study revealed changes in the optimal management equilibrium represented by optimal basal area, tree species composition, diameter distribution and target harvest diameter over time due to the adapted ecological modelling. The main lesson of the past for the future is to avoid placing too much trust in the simple extrapolation of current trends, such as the observed continual decline in spruce related to climate change, but to be aware of temporal and possibly reversible processes, such as the observed extensive fir recovery after the reduction of air pollution. Tree species diversity appears to be the best option for the uncertain future.

Key words: Subplex algorithm; simultaneous nonlinear optimisation; matrix transition model; near-natural forestry; uneven-aged management

Editor: Bohdan Konôpka

1. Introduction

Climate change has already increased the temperature in Europe by approximately 1.0 °C compared with the pre-industrial level and is expected to continue to become more intensive in the next centuries (IPCC 2018). Climate change is strongly changing ecological conditions, influencing the growth conditions of tree species; therefore, it is a challenge for forest management planning because not all experiences from the past decades or the last centuries are useful under the new conditions.
Nevertheless, direct relations from changes in temperature or precipitation into changes in ecological characteristics of tree species, such as increments in diameter at breast height (*dbh*), regeneration frequency, and mortality rate are not easily possible, but their correlated trends can be shown, e.g., by Bošeľa et al. (2019).

Learning from the past, it is possible to identify trends and extrapolate these trends to the future. This process is not directly possible as climate change is not a linear but a fluctuating process. In addition to climate change, other changing aspects such as management, air pollution loads, or game browsing are influencing tree health and growth (Bošeľa et al. 2019).

In addition to the direct impact of climate change on the growth and productivity of tree species, climate change also increases the frequency and intensity of natural disturbances (Seidl et al. 2014). In the forests on the Western Carpathian Mountains, disturbances occur mainly in old even-aged spruce forests (Hlásny et al. 2017). Uneven-aged mixed forests are more stable under climate change (Griess et al. 2012; Roessiger et al. 2013). Nevertheless, yield tables often underestimate growth and are only suitable for even-aged single species

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management planning (Pretzsch et al. 2014). Solutions for forest management planning are growth simulators such as the matrix transition model (e.g., Usher 1969), which also includes density-dependence (Buongiorno & Michie 1980). The matrix transition model is a simulator to predict population dynamics (Lewis 1942; Leslie 1945). Applied to uneven-aged forestry, the model is able to implement actual inventory data structured into *dbh* classes (Buongiorno & Michie 1980) rather than age. Matrix transition models typically consist of ecological models such as 1) transition probabilities to the next higher *dbh* class, 2) ingrowth frequencies in the lowest *dbh* class, and 3) mortality probabilities by *dbh* classes to predict overall stand development.

Liang et al. (2011) applied matrix modelling to estimate expected forest dynamics under climate change, e.g., regarding changes in species composition in the Alaska coastal forest, which is sensitive to site productivity, plot elevation, plot aspects, and total stand basal area (*ba*), but also the mean temperature and precipitation during the growing season.

Growth trends of species under climate change are also evident in the regional findings of Bosela et al. (2019). To consider such growth trends in management planning tools, they were implemented into the matrix transition model of Roessiger et al. (2018). By using a harvest optimiser included in the simulation, a goal towards optimal forest management can be determined. A planning goal is an equilibrium defined as a hypothetical long-term stable species and diameter distribution under assumed stable conditions to achieve the highest continuous financial yield. The purpose is to estimate the sensitivity of this equilibrium under the changing climate. The intention is to confirm the hypothesis: equilibrium states of *ba*, species composition, *dbh* distribution, and target harvest *dbh* in the mixed uneven-aged forest fluctuate and are sensitive to changes in ecological growth conditions over time.

2. Material and methods

2.1. Study area

The study area represents the “Pro Silva” model forest unit Smolnícka Osada covering 2,132 hectares of forest in the Volovské Mountains in the Central West Carpathians (48°44’ N, 20°46’ E). The altitude ranges from 440 to 1,150 m above sea level, the geological bedrock is formed mainly by phyllites with a dominant representation of dystric and typical cambisols (Kulla et al. 2017). The territory was affected by acid air pollution from remote sources combined with local pollution from metal processing industries, which culminated in the 1980s and decreased significantly in the 1990s. Mixed, continuous-cover, single-tree to group selective forestry, so-called plenter forest management, was established since 1950 in the mixed beech-fir-spruce forests with admixed pine, resulting in uneven-aged forest structures with spontaneous natural regeneration of beech, spruce and fir. Particularly, fir regeneration has been increasingly damaged by the continually rising population of ungulate game since the 1960s.

The region is structured in three strata: stratum A is the biggest and represents the upper altitudinal belt dominated by beech and fir with spruce admixture; stratum B is situated in the lower altitudinal belt dominated by spruce and older pines with fir and beech admixture, which was influenced by pasturing in the past centuries; and stratum X represents smaller protective forests on exposed sites spread over the total study region with various species composition (Kulla et al. 2018).

2.2. Growth history

Using tree-ring methods, Bosela et al. (2019) evaluated the effects of changed environmental conditions in the model forest unit on long-term changes in radial increments during a period from 1900 – 2014. Input for this study was tree-ring samples from 319 beeches, 283 firs, 111 spruces, and 64 pines from Smolnícka Osada in 2014. The measured tree ring widths were transformed into basal area increments of a single tree (*bai*). Conversion of tree-ring width into *bai* removes biases of productivity estimates (Bouriaud et al. 2015). Further, *bai* better correlates to the volume added to circular stems than tree ring width (Biondi & Qedan 2008).

A generalised additive mixed model was used to compare *bai* of four species in mixture and altitudinal (lower than and higher than 800 m a.s.l) categories. A linear mixed-effect model was used to estimate the effects of *dbh*, temperature, precipitation, and crown characteristics on *bai* variation and to test the effects of climate, competition and species diversity on *bai* variation (Bosela et al. 2019).

The species-specific forest growth history was typified as follows:

– high spruce increment at the beginning of the 20th century followed by a strong decline of spruce during the last decades,
– relatively stable beech increment with a slight increase and some fluctuation,
– an apparent minimum of fir increment in 1980 caused by the emission load of heavy metals such as mercury, lead, and arsenic elements, followed by a substantial recovery of fir due to both the warmer climate and reduced air pollution,
– a moderate decline of the pine increment since the middle of the last century.

2.3. Matrix transition model

The matrix model of Roessiger et al. (2018) was based on an inventory of the model forest unit in the year 2014

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on 344 inventory plots. Typically, regression of transition, ingrowth, and mortality requires two inventories to estimate the differences within a period. Therefore, an inventory was recalculated for the year 2004 by Kulla et al. (2017). This inventory serves as a reference.

Each step to simulate a new stand structure is ten years. The *dbh* – class width is 4 cm, and the model comprises *dbh* classes with class means from 10 to 98 cm.

The typical matrix model (Buongiorno & Michie 1980) is extended to specify the ideas of modelling by Roessiger et al. (2016, 2018): individual sub-models consider tree species of beech, fir, spruce, and pine; crown characteristics (section 2.5.1); as well as stem characteristics (section 2.6).

The matrix model was applied individually for four case studies in example years 1910, 1950, 1980, and 2014, each representing a historical phase of stand development. The matrix model was used for simulation and detection of an optimal equilibrium state that is sensitive to growth conditions typical for the preselected example years in the growth history. The matrix model was based on or adapted from Roessiger et al. (2018) and Kulla et al. (2018). Matrix modelling was adapted stepwise to demonstrate the effects of single changes of inputs in four studies. In the first step, only the transition probabilities (T, section 2.5.1) were adapted, with further ingrowth (I, section 2.5.2) and then mortality (M, section 2.5.3), concluded by a case study on ingrowth reduction by game browsing (G, 2.5.4). A financial evaluation (section 2.6) allowed financial optimisation of the harvest (section 2.7).

2.4. Modelling of historical increments and historical inventory data

The matrix model requires a *dbh* scale. Therefore, it was necessary to again retransfer the final value of *bai* for an example year by Bošeľa et al. (2019) to the unit of the *dbh* increment.

The coefficient $I_{m,y}/I_{m,2014}$ represents the mean (m) of the *dbh* increment $I_{m,y}$ (Table 1) for a species in an example year (y) relative to the reference year 2014 $I_{m,2014}$.

In the original inventory dataset, the decennial *dbh* increment $I_{n,2014}$ between years 2004 and 2014 for each single tree n was multiplied by the coefficient $I_{m,y}/I_{m,2014}$ for a specific example year to derive an individual *dbh* increment of $I_{n,y}$ for this tree. This modelling ensures that the proportions between single trees remain the same independently of the example year.

$$I_{n,y} = I_{n,2014} * I_{m,y}/I_{m,2014};\ y = 1910; 1950; 1980; 2014$$

Each single tree *dbh* from the first year of inventory (2004) was added with the adapted increment $I_{n,y}$ to calculate the hypothetical individual *dbh* in the second year. In this way, the specific virtual inventory data set prepared for matrix modelling was obtained for each example year. This modelling indicates a simplification, but the real *ba* and initial stand state composition were unknown for the historical states.

2.5. Matrix sub-models adapted by the historical change in increment

2.5.1. Transition adapted by the historical change in increment

The transition (study T) describes the change for a tree from the current to a higher *dbh* class within ten years and is estimated as probability. Typically, the transition occurs to the next *dbh* class, and the remaining proportion stays in the same *dbh* class. Roessiger et al. (2018) allowed trees with long crowns to transition to the next or next-but-one *dbh* class due to their correlation with improved growth. For this purpose, two classes for a crown proportion length longer and shorter than 2/3 of the tree height were distinguished and consistently applied to each tree species except pine, which had only short crowns. Although the transition to the next-but-one

Table 1. Increment data published by Bosela et al. (2019) related to strata in the model territory by Kulla et al. (2018), and the derived coefficient $I_{m,y}$ and $I_{m,y}/I_{m,2014}$ used for model adaptation.

Altitude and respective stratum	Tree species	Example year	Basal area increment *bai* [cm² year⁻¹]	Diameter increment $I_{m,y}$ [cm year⁻¹]	$I_{m,y}/I_{m,2014}$ increment relative to year 2014
Higher than 800 m (stratum A)	Beech	1910	10	3.568	0.79
		1950	13	4.068	0.90
		1980	13	4.068	0.90
		2014	16	4.514	1.00
	Fir	1910	15	4.370	0.89
		1950	13	4.068	0.83
		1980	7	2.985	0.61
		2014	19	4.918	1.00
	Spruce	1910	45	7.569	2.54
		1950	33	6.482	2.17
		1980	19	4.918	1.65
		2014	7	2.985	1.00
Lower than 800 m (stratum B)	Pine	1910	13	4.068	1.20
		1950	12	3.909	1.15
		1980	11	3.742	1.11
		2014	9	3.385	1.00

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dbh class is a violation of the Usher assumption (Usher 1969), it had already been applied by Solomon et al. (1986) and Roessiger et al. (2016, 2018).

Based on the adapted dataset (Kulla et al. 2018), a binary logistic regression was applied because of the benefit of allowing only transition probabilities between 0 and 1. Regression was carried out for generalised linear models via the R function "glm" (R Core Team 2015). The transition probability depended on *dbh* and *ba,* except for spruce, which only depended on *ba* (Table 2).

$$p = 1/\left(1 + exp\left(-(c_0 + c_1 * dbh + c_2 * ba)\right)\right)$$

2.5.2. Expected ingrowth positively correlated to increment

Adaptation of historical transition was based on the measurements of Bosela et al. (2019), but transition alone cannot represent the complete change in species characteristics over time. Ingrowth frequency represents the number of trees passing the *dbh* of 8 cm within ten years. Because of the unknown ingrowth in the past, the assumption was accepted that *dbh* increments indicate the general health state of the species and that ingrowth is positively correlated with the *dbh* increment. The Weibull (2–parameter) probability density function for ingrowth (*ING*) of Roessiger et al. (2018) for data of all stratum was multiplied by the coefficient $I_{m,y}$ of the stratum higher than 800 m (Table 1) to derive study (I). The coefficients are the scale parameter λ, the shape parameter κ (fixed to value 2), and a calibration parameter *c* to adapt the x–axis to represent higher *ba* values. Regression was carried out with the "nls" function (an R package "minpack.lm" based on a nonlinear least-squares algorithm) in R software (R Core Team 2015). Coefficients for λ were 0.0277, 0.0728, 0.0324, and for *c* 1094, 508, 445, for beech, fir and spruce, respectively.

$$ING = \frac{\kappa}{\lambda}\left(\frac{ba/c}{\lambda}\right)^{\kappa-1} * exp^{-\left(\frac{ba/c}{\lambda}\right)^{\kappa}} * I_{m,y}$$

Only ingrowth from plots with at least one seed tree of more than 40 cm was considered in the regression. As a result, ingrowth was low for a *ba* of 0 and for a very high *ba*, with the maximum observed for a species-specific optimal *ba*. Optimal *ba* was highest for shade-tolerant fir with 26 m^2/ha and beech with 21 m^2/ha and lowest for spruce with 10 m^2/ha. Pine ingrowth was set to 0 as it had no sufficient ingrowth under the canopy of shade-tolerant species during succession.

A binary logistic regression (as used for transition) that was sensitive only to *ba* separated ingrowth into crown classes. In the case of low *ba*, a higher proportion had a long crown. The regression coefficients for the *Intercept* were 0.82, 1.39, −0.544 and for *ba* −0.0058, −0.0352, −0.0111 for beech, fir, and spruce, respectively.

2.5.3. Expected mortality negatively correlated to increment

Similar to transition, adaptation of the mortality (study M) data for reference inventory was applied based on observed increment dynamics. Mortality is the probability of trees naturally dying every ten years. Single tree mortality is assumed to negatively correlate with the health state and *dbh* increment in the past.

Table 2. Coefficients of the binary logistic regression of transition probability and their statistics (database described in section 2.4).

Species crown class	Coefficient	1910 Estimate	1910 Sign. Level	1950 Estimate	1950 Sign. Level	1980 Estimate	1980 Sign. Level	2014 Estimate	2014 Sign. Level
Beech short crown	*Intercept*	0.792	**	1.233	***	1.233	***	2.3	***
	dbh	0.0409	***	0.0594	***	0.0594	***	0.0708	***
	ba	−0.021	*	−0.0325	***	−0.0325	***	−0.0532	***
Beech long crown	*Intercept*	−1.971	***	−1.42	***	−1.42	***	−1.06	***
	dbh	0.0499	***	0.0424	***	0.0424	***	0.0433	***
	ba	−0.128	***	−0.0926	***	−0.0926	***	−0.0747	***
Fir short crown	*Intercept*	−0.0002		−0.216		−0.903	***	0.75	*
	dbh	0.0572	***	0.0507	***	0.0458	***	0.0653	***
	ba	−0.0222	**	−0.0166	*	−0.0133	*	−0.0347	***
Fir long crown	*Intercept*	−0.818	**	−0.942	***	−0.588	.	−0.455	.
	dbh	0.0615	***	0.0594	***	0.0414	***	0.0616	***
	ba	−0.0341	***	−0.0372	***	−0.0739	***	−0.0304	***
Pine	*Intercept*	1.108	*	1.145	*	1.104	*	0.927	.
	dbh	0.026	*	0.0209	.	0.0191	.	0.0182	.
	ba	−0.0226	*	−0.021	.	−0.0209	.	−0.0198	.
Spruce short crown	*Intercept*	3.7	***	3.022	***	2.202	***	0.8652	*
	ba	−0.064	***	−0.0711	***	−0.0673	***	−0.0505	***
Spruce long crown	*Intercept*	5.447	***	4.554	***	3.562	***	0.1784	
	ba	−0.191	***	−0.178	***	−0.176	***	−0.1063	**

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

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Original mortality probabilities $M\_p_{n,y}$ (with n as the single salvage proportions derived from forest stand management records of all strata) specific for species and the mean *dbh* of a stand layer were divided by the coefficient $I_{m,y}$. The only restriction was a maximum salvage proportion of 100%, but it was relevant to adaptation only for 5 of the 673 cases of fir. The other species did not need the correction.

$$M\_p_{n,y} = M\_p_{n,2014} / I_{m,y};\ y = 1910;\ 1950;\ 1980;\ 2014;\quad 0 \leq M\_p_{n,y} \leq 1$$

Using the adapted mortality data from all strata, a binary logistic regression utilising the "glm" function in R (R Core Team 2015) was applied to estimate the probability of mortality dependent on *dbh* (Table 3).

$$p = 1/\left(1 + exp\left(-(c_0 + c_1 * dbh)\right)\right)$$

2.5.4. Case study of reduced ingrowth due to increased game browsing

To consider the increased game density and browsing in the last decades starting in the 1960s, the observed ingrowth of fir in study I was increased by 100% (doubled) for year 1910 and 1950, by 50% for year 1980 and remained as observed for year 2014 for study G.

2.6. Financial evaluation

The financial value of a tree is considered a net cash flow (*NCF*) per tree stem. *NCF* is calculated as the net timber price related to the timber volume per stem (Petráš & Pajtík 1991). The net timber price is the timber price based on tree assortment tables that are sensitive to species, stem quality, and stem damage, as reported by Petráš et al. (2017), minus harvest costs including 8.92 €/hour related to time using standards (Ministry for Forest and Water Management of the Slovak Republic, 1992a, 1992b), actual hour rates and chain saw compensation, plus 2.15 € m^{-3} tractor compensation.

Further sub-division within each species are the individual *NCF* for two classes distinguished by good and bad stem quality considering also stem damage. Ingrowth was allocated to the stem classes by fixed proportions observed by the reference inventory. Good stems were 34% of beech, 58% of fir, 41% of spruce, and 71% of pine.

The resulting net timber prices per stem were 10 – 14 € for a *dbh* of 10 cm, 80 – 140 € for a *dbh* of 42 cm, and 250 – 350 € for a *dbh* of 66 cm. Prices were lower for bad stems and higher for spruce and fir compared with pine and beech.

In the case of mortality, only 75% of *NCF* was considered in the financial evaluation.

A simulation step *t* was ten years, within a total simulation period *T* of 400 years. The harvest cycle was 20 years. A single *NCF* was calculated separately for each possible combination of each individual species, crown, stem, and *dbh* class *c* of all combinations of these classes *C* for a given *t*. *NCF* was calculated for standing tree *NCF*s, for trees failed by mortality *NCFm*, and for trees harvested *NCFh*. Mortal timber dying over a period of two decades (*NCFm1* and *NCFm2*) was summarised and was harvested together with the following planned harvest.

A concept to evaluate total financial stand performance over time is the net present value (*NPV*). *NPV* was adjusted by holding value (Deegen et al. 2000), which was already used by Roessiger et al. (2016 and 2018). This type of *NPV* considers the financial value of the remaining stand at the beginning and end to ensure that no clearcut was ultimately conducted. Each single *NCF* was discounted by an interest rate *i* of 2%.

$$NPV_{C,T=400} = \sum_{c}^{C} \left(-NCFs_{c,t=0} + \sum_{t=0}^{T-20} \left(\frac{NCFh_{c,t}}{(1+i)^t} + \frac{NCFm1_{c,t}}{(1+i)^{t+20}} + \frac{NCFm2_{c,t+10}}{(1+i)^{t+20}} \right) + \frac{NCFs_{c,T}}{(1+i)^T} \right)$$

2.7. Financial optimisation

The optimisation objective to estimate the optimal harvest strategy was a maximisation of *NPV*. Optimisation means to test the harvest by testing all combinations *C* in all periods *t* simultaneously and to choose only the combination that results in the maximum *NPV*. Harvest optimisation was carried out within the simulation framework by using the Subplex algorithm of Rowan (1990) implemented into the R programme (R Core Team 2015) by King (2015).

Table 3. Coefficients of binary logistic regression of mortality probability and their statistics, (database described in section 2.4).

Species	Coefficient	1910		1950		1980		2014	
		Estimate	Sign. Level	Estimate	Sign. Level	Estimate	Sign. Level	Estimate	Sign. Level
Beech	*Intercept*	−6.966	***	−7.097	***	−7.097	***	−7.2	***
	dbh	0.0645	*	0.0645	.	0.0645	.	0.0644	.
Fir	*Intercept*	−4.429	***	−4.360	***	−4.069	***	−4.542	***
	dbh	0.0451	*	0.0452	**	0.0462	**	0.0448	*
Pine	*Intercept*	−5.622	.	−5.582	.	−5.538	.	−5.438	.
	dbh	0.0306		0.0306		0.0306		0.0307	
Spruce	*Intercept*	−4.818	***	−4.673	***	−4.421	***	−3.996	***
	dbh	0.0754	***	0.0763	***	0.0785	***	0.0849	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

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The Subplex algorithm requires technical constraint by harvesting only a proportion between 0% and 100% of existing trees in each *dbh* class before each simulation step. This constraint is achieved by an "*If*" function entry with a high negative value in the case of harvesting more trees than exist or a negative number of trees. Subplex minimises the goal function, therefore minimising a technically negative *NPV*.

Only the equilibrium in year 240 before the harvest was used for results to represent typical stable mean conditions excluding two types of fluctuations that typically occur during the optimisation cycle. 1. At the beginning of the optimisation, the species and diameter distribution changed from the known initial state in 2004 to the optimal state. 2. At the end of the optimisation, *ba* increased, caused by the lack of necessity for future investment in ingrowth (Roessiger et al. 2018).

3. Results

The results are presented as a comparison of the optimised management equilibrium characterised by *ba*, harvest, *dbh* distribution and target *dbh* by species for the four different cases described above (T, I, M, G) and for different times represented by four example years (1910, 1950, 1980, 2014).

The cases are defined as additional, according to the extent of adaptations regarded in the matrix modelling:

R – reference study of year 2014 based only on observed data without adaptations,
T – includes R and only adapted transition probabilities related to historical increment data,
I – includes R, T plus adapted ingrowth frequencies correlated positively to diameter growth,
M – includes R, T, I, plus adapted mortality rates correlated negatively to diameter growth,
G – includes R, T, I, M, plus consideration of reduced game browsing of fir in the past.

For year 2014, R is identical to T, I, M, and G and, therefore, only presented once. Essential results concerning optimal *ba* and optimal harvest including financial value are presented for all cases. Detailed results for diameter distribution and target diameters are provided as examples for case T as the most methodologically clean case supported by historical data, and for case G, which, even if based on more assumptions, is hypothetically the most realistic.

3.1. Differences in optimal stand basal area, mortality and financial value of the harvest

Comparing the four studies for the example years regarding the remaining stand indicates in terms of the species ecology, a lower *ba* was related to a higher spruce proportion, while a higher *ba* was related to higher beech and mainly higher fir proportions. Modelling of the light-demanding spruce showed the most intensively positive reaction to changes, especially on I but also on M, as occurred at the beginning of the last century. The spruce decline during the evaluated time period was rapid, and a trend extrapolation would lead to complete spruce extinction in the study region in the future, as already projected for pine due to missing pine ingrowth.

In G 1910, the *ba* of fir was two times higher compared with M 1910, although the fir target *dbh* structure was the same. The cause was the lower browsing by game. Fir *ba* declined until 1980 and then came back until 2014, which would have been more intensive if fir ingrowth had not been limited by recent game browsing. Beech became more dominant with each time step (Fig. 1).

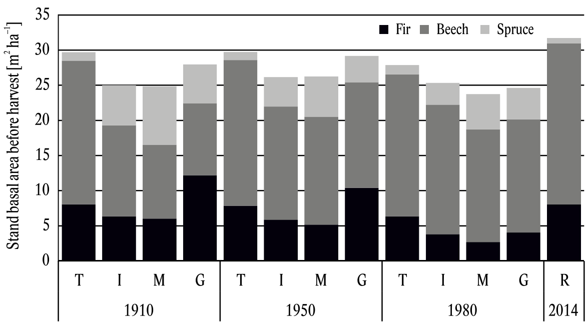

Fig. 1. Optimal stand basal area in the optimised equilibrium state before harvest for the different example years.

Ba summarising timber failed by mortality (Fig. 2) was strongly distinguished from the *ba* standing. Although beech formed the majority of the *ba* proportion of G since 1950, it had a relatively low mortality probability. In studies T and G, fir had the highest proportion of mortality from *ba* in all example years except 1980. The reason for the high fir mortality was its high-value increment potential; therefore, the optimiser allowing fir to reach a high target *dbh* (Fig. 4) correlated with the naturally increasing probability of mortality, although fir mortality rates, in fact, were significantly lower compared with those of spruce.

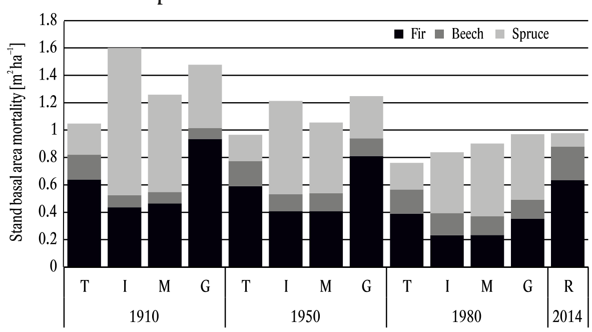

Fig. 2. Basal area of mortality in the optimised equilibrium state for a 20-year harvest cycle for the different example years.

The financial value of the fir harvest was higher compared with the respective proportions of *ba* because the net timber price of the fir harvest increased over-pro-

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portionally to the higher target *dbh* (see also Fig. 6). For spruce characterised by a lower target *dbh*, the proportion of financial value was lower than the respective *ba* proportion. For study G in 1910, fir formed the main proportion of the financial value of the harvest (Fig. 3).

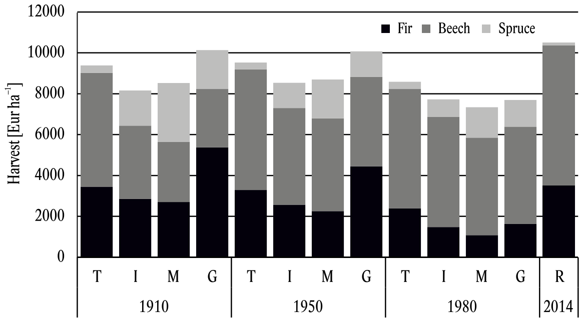

Fig. 3. Financial value of the optimal harvested part of the stand in the equilibrium state for a 20-year harvest cycle.

3.2. Differences in optimal diameter distribution

In study T, conditions for spruce were best in the year 1910, resulting in a relatively fast transition compared with the other years. In 1980, a large number of firs accumulated in the lower *dbh* classes and did not transit to the next *dbh* class because fir transition probability was low in comparison to other years due to culminating air pollution. In the year 2014, the *dbh* distribution became flatter because the beech and fir trees in lower *dbh* classes transited more rapidly to higher classes and the target *dbh* was higher (Fig. 4).

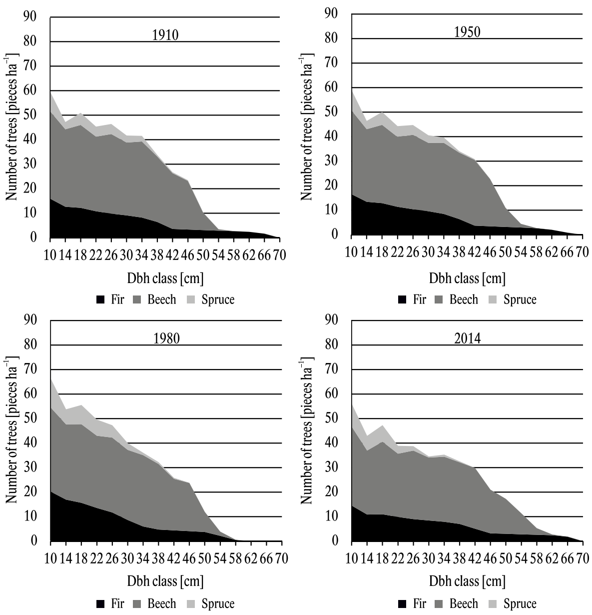

Fig. 4. Differences in optimal diameter distribution in equilibrium to study only the adaptation of transition probability supported by historical increment data.

For study G compared with T, the *dbh* distribution of beech became steeper and excluded higher *dbh* classes for earlier example years. Both changes were caused by lower ingrowth and higher mortality involved through regarded expectations about the correlation of these processes with increment dynamics. The same worse conditions as observed for beech at the beginning of the last century were experienced by fir, but fir was supported by double ingrowth thanks to the assumption about lowered game browsing in 1910 and 1950; otherwise it was comparable to beech.

The number of ingrowths by species entering the lowest *dbh* class depended on the actual *ba*, actual ingrowth rates, and species shade tolerance in the order fir– beech – spruce. For the G case, beech ingrowth was nearly constant, spruce ingrowth profited in 1910 from spruce vitality and in 1980 from lowered *ba* due to the fir decline, and fir ingrowth continuously decreased due to the increasing game browsing (Fig. 5).

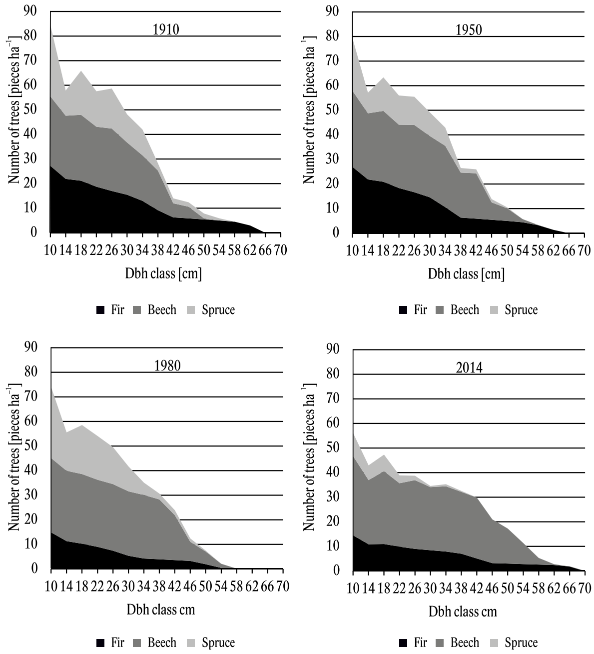

Fig. 5. Differences in optimal diameter distribution in equilibrium for the case applying all adaptations based on historical data and all sets of predefined expectations.

3.3. Differences in target harvest diameter

The change in target *dbh* over time within one tree species depends especially on the change in transition probabilities determining the value increment, as well as mortality lowering timber price. For beech, from year 1910 up to 2014, stability or an increase in target *dbh* for all classes was achieved. The target *dbh* of the fir classes was nearly constant in the years 1910, 1950, and 2014. The year 1980 saw a reduction in all fir classes. The target *dbh* of long crown firs reached up to 12 cm lower compared with 2014. The spruce target *dbh* declined continually from 1910 to 2014 (Fig. 6).

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When comparing study I to study T, some beech and fir classes in 1910 and 1950 showed a decreased target *dbh* by 4 cm. The driver decreasing the target *dbh* before 1980 was the lower ecological potential of beech and fir to produce ingrowth. The optimiser decided for a lower *ba* to support ingrowth to balance the lacking ingrowth before 1980. Due to the fir decline in 1980, the fir target *dbh* and *ba* were already lower compared with other years, and the low *ba* did not depend on a decrease in the target *dbh* of beech. Only spruce showed cases with an increased target *dbh* by 4 cm in 1980 because the light-demanding spruce benefited from the lower *ba*.

In study M compared with study I, further changes in target *dbh* appeared. Some cases of target *dbh* of fir and beech classes declined by 4 cm due to higher mortality in the earlier years. In the cases of spruce classes, target *dbh* increased by 4 cm (Fig. 6). Nevertheless, the changes in target *dbh* from I to M in combination did not change *ba* but changed proportions of *ba*. Spruce showed an increased proportion due to lower mortality, while fir showed decreased proportions due to higher mortality. The beech proportion remained constant in 1950 and 1980 and slightly declined in 1910 (Fig. 1).

4. Discussion

4.1. Not considering the effects of changed management and ecological succession

The results revealed changing states of the optimal *dbh* distribution and species composition of an optimised equilibrium resulting from changing growth conditions and, consequently, changing increments over time. The main reason for these changes in the region of interest might be climate, especially temperature, the carbon dioxide concentration in the atmosphere and the emission load of heavy metal (Bosela et al. 2019).

Pretzsch et al. (2014) found an increase in increment for beech and especially young spruce in Central Europe since 1870. Additionally, Šimůnek et al. (2019) showed positive relation of the beech increment to a higher temperature in Krkonoše National Park (North of Czech Republic). Vacek et al. (2019) demonstrated a strong decrease in spruce increment between 1978 and 1987 as result of the air pollution load of sulphur (SO_2) in Jizerské Hory Mountains (North of Czech Republic), followed by spruce recovery. While beech results for Smolnícka Osada are in accordance with the findings of Pretzsch et al. (2014), spruce, in contrast, showed a strong linear decline. Bosela et al. (2019) demonstrated the negative effect of increased temperature on the spruce increment. Hence, some additional locally specific factors including

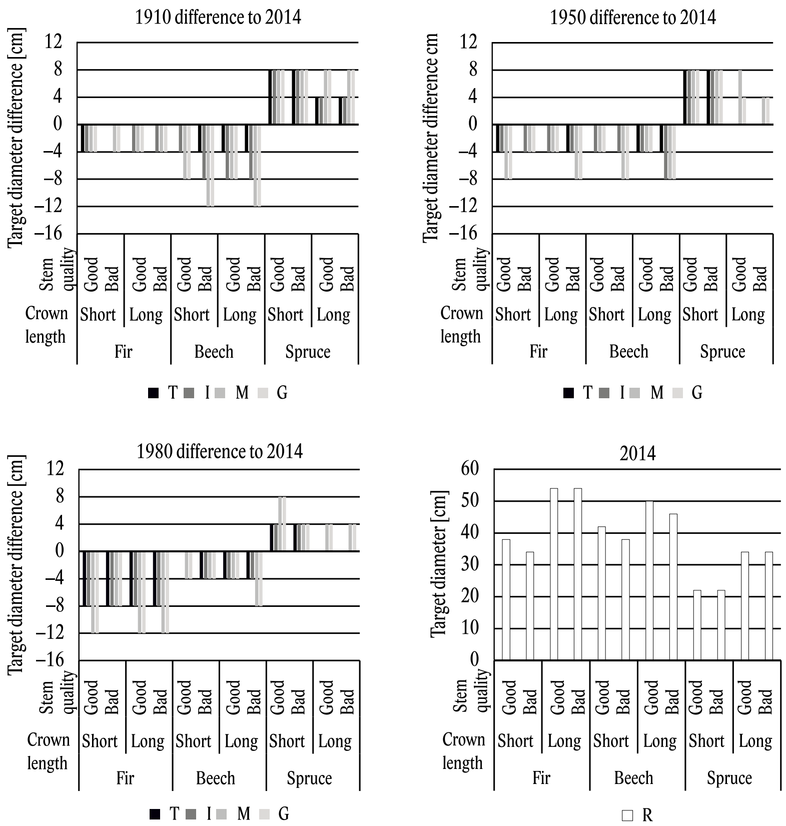

Fig. 6. Differences in target diameter in equilibrium with adaptations based on historical data and all sets of predefined expectations (crown classes: long, short; stem classes: good, bad).

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changed management might be a reason for the different trend of the spruce increment in the study of Smolnícka Osada.

Regardless, changed management is responsible for the continuous decline of pine. As a strongly light-demanding species, pine benefited from the free land conditions and low *ba* in the past. A change to plenter forest management since 1950 supported shade-tolerant species and limited light-demanding species.

The ecological succession develops from the light-demanding tree species pine over spruce to the shade-tolerant species beech and fir. Spruce is currently disappearing, as the main species have become beech and fir. The process is still progressive in stratum B. Nevertheless, today there are strong differences between the ecological characteristics of stratum A characterised by high beech ingrowth and stratum B characterised by high spruce ingrowth (Kulla et al. 2018).

The changed management, ecological succession, and their impacts on ecology could not be considered in Smolnícka Osada study because detailed data about the initial stand and true ecological models of ingrowth and mortality in the past are unknown and can only be assumed. Nevertheless, sensitivity studies of the ecological and management models are generally applied to identify the extent to which the matrix models react to changes, e.g., Ficko et al. (2016, 2018) applied management assumptions of no management, business-as-usual, profit maximisation, and maximisation of the number of firs in the smallest *dbh* class to three Slovenian regions.

4.2. Interpretation of simplified expectations to adapt ecological models

Typically, the increment is an indicator of the health state and thus should indirectly positively correlate with ingrowth frequency and negatively correlate with the single tree mortality probability. The single tree mortality is a characteristic of close-to-nature and continuous-cover forestry and represents a different situation compared to stand-wise calamity. Calamity should partly positively correlate with increment due to the increased exposure to storm by the increased tree height or due to bark beetles by increased tree *dbh*, given the same stand age. Excluding on some small proportions of pure spruce stand, there is less calamity but more single tree mortality dominating in the study region.

Nevertheless, these correlations are assumptions, and the real ingrowth frequency and mortality probability during the evaluated historical time periods are unknown. Further, the historical initial stand state, timber prices and harvest costs are also unknown and are assumed to be constant and consistent with the current ones in the study of Smolnícka Osada.

Due to the unknown mortality and ingrowth, only study T, which adapted solely transition, represents a real estimated change. Studies I and M represent a frame of unknown but possible outputs rather than the expectation of the same values as in the year 2014. In addition, they allow testing of the sensitivity and limits of the advanced matrix modelling approach to search for the economically optimal equilibrium for uneven-aged forest management.

Study G might represent a case study concerning how a sufficient hunting regime might influence management, especially via improved conditions for fir. Our results signify that if the increasing negative influence of game on fir ingrowth tested in study G would not exist, the *ba* as well as the financial value of forest would be higher than actually observed. Research on optimising *ba* to improve fir ingrowth in three Slovenian regions resulted in an increase in the number of firs in small *dbh* classes, but it was not sufficient in the case of high game pressure, as reported by Ficko et al. (2016).

5. Conclusion

The results of this study confirm that the optimal equilibrium of the uneven-aged forest can fluctuate over time as a consequence of changing environmental conditions. This study mainly shows trends of tree species development, which can be extrapolated to support planning for possible climatic conditions that are expected to appear in the future in the study region. Trusting tree species that are unsuitable under climate change might lead to a degradation of forests. Climate change forces the long-term adaptation of management. An adaptive management policy might even require the use and intermixing of native and non-native tree species (Bolte et al. 2009).

The optimality of equilibrium states reached by means of optimisation can only be a "temporal pseudo-goal state" that varies over time. Consequently, it should be interpreted more as a direction of development of forest management than as a goal that must be immediately reached. This goal should be updated within regular planning intervals, typically when new inventory data are available. Such updates can be part of adaptive forest management related to "learning by doing" in the sense of Gadow (2006).

To allow options to adapt, management-sufficient possibilities must be available.

Nevertheless, the case of the rapid short-term fir decline around the year 1980 and its revitalisation demonstrates that some trends are reversible. A simple extrapolation of this temporal trend and its implementation into management planning would have led to the loss of fir in the study region. Therefore, especially for management relying on natural regeneration, changes in forest composition that are too fundamental and rapid can lead to an almost irreversible loss of a tree species that might be beneficial for until now not known future conditions.

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Further, it is beneficial to maintain a high species diversity even when some tree species are under pressure during the phases of forest development. Mixed, uneven-aged, close-to-nature, and plenter management are the best options to prepare for future uncertainty by allowing small and continuous changes in species composition using natural regeneration. Flexible management must always adapt to temporal changes but may not completely trust in temporal trends, while retaining the fundamental criteria for sustainability.

Acknowledgements

This work was supported by the Slovak Research and Development Agency (Projects APVV-18-0195 SilvaMod and APVV-15-0265 DENDROCLIM: 80%); and by the Ministry of Agriculture and Rural Development of the Slovak Republic (Item No. 08V0301- Project SLOVLES: 20%).

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Cent. Eur. For. J. 65 (2019) 191–197 sciendo DOI: 10.2478/forj-2019-0014

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Predicting forest stand variables from airborne LiDAR data using a tree detection method in Central European forests

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Abstract

In this study, the individual tree detection approach (ITD) was used to estimate forest stand variables, such as mean height, mean diameter, and total volume. Specifically, we applied the multisource-based method implemented in reFLex software (National Forest Centre, Slovakia) which uses all the information contained in the original point cloud and a priori information. For the accuracy assessment, four reference forest stands with different types of species mixture and the area of 7.5 ha were selected and measured. Furthermore, independent measurements of 1 372 trees were made for the construction of allometric models. The author's ITD-based method provided slightly more accurate estimations for stands with substantial or moderate dominance of coniferous trees. However, no statistically significant effect of species mix on the overall accuracy was confirmed ($p < 0.05$). The root mean square error did not exceed 1.9 m for mean height, 3.0 cm for mean diameter, and 12.88 m^3 ha^{-1} for total volume.

Key words: forest inventory; airborne laser scanning; individual tree detection; multisource-based method

Editor: Peter Surový

1. Introduction

In recent years, airborne laser scanning (ALS, also called airborne LiDAR), has developed to an effective technology for predicting forest stand variables. This is primarily because a laser beam used by these systems can penetrate even through the dense and multi-layered forest canopies to the ground, and ALS data can be used for direct estimate of a spatially explicit three-dimensional canopy structure with sub-meter accuracy (Ginzler & Waser 2017).

A comprehensive overview of ALS-based applications in forestry was published by Maltamo et al. (2014) and current state-of-the-art was examined by Surový & Kuželka (2019). These reviews, as well as other studies, reported accuracy ranging between 32–89% for individual tree detection (Kaartinen et al. 2013; Jeronimo et al. 2018), 6–33% for tree heights estimation (Awaya & Takahashi 2017; Jin et al. 2018), 16–46% for tree diameters derivation (Holopainen et al. 2010; Preditis et al. 2012), and 10–42% for growing stock estimation (Hansen et al. 2017; Kandare et al. 2017).

This study focused on predicting forest stand variables from ALS data using individual tree detection approach (ITD). ITD-based techniques usually involve a sequence of tree detection, feature extraction, and estimation of tree attributes. In general, tree tops/crowns and tree heights are extracted directly from ALS data or ALS-based derivatives, whereas other biophysical attributes are inferred indirectly through allometric models. However, the stand variables that are directly linked to the number of detected trees are often underestimated due to problems with detection of suppressed and understory trees. To solve this problem, semi-ITD approaches and several techniques for modelling understory trees have been proposed (e.g., Lahivaara et al. 2014; Melville et al. 2015; Kansanen et al. 2016).

Many algorithms related to the ITD approach have been developed to predict forest stand variables (e.g., Apostol et al. 2016; Dalponte et al. 2017). In this study, we applied our own multisource-based method implemented in reFLex software (National Forest Centre, Slovakia). The algorithm attempts to eliminate several shortcomings of the current ITD-based methods through the following improvements: (i) the algorithm uses the complete information contained in ALS data in all procedures of tree detection workflow, and optimizes the computationally demanding operations by tiling and thinning techniques applied on the original ALS data, (ii) treetops detection and tree crowns delineation is done iteratively, and each iteration includes tests for

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treetop verification based on tree allometry rules, aiming at reduction of incorrectly detected trees, (iii) users can modify a number of parameters and customize the algorithm for matching specific stand conditions and/or meeting specific objectives.

The overall objective of the study was to use an author's ITD-based method to estimate forest stand variables in heterogeneous Central European forests with various species mixtures. We focused on main forest stand variables, namely mean height, mean diameter, and total volume.

2. Materials and methods

The study area (Fig. 1) is a part of the University Forest Enterprise of the Technical University in Zvolen, located in central Slovakia (48°37´N, 19°05´E). Discrete airborne LiDAR data and two independent groups of field data were available for the whole study area: (i) ground calibration data for construction of allometric models and (ii) ground reference data for validation of method.

2.1. Airborne LiDAR data

ALS data acquisition was performed in September 2011 using a Riegl L-680i scanner. The study area was scanned from an altitude of 700 m with a 60° field of view, 320 kHz laser pulse repetition rate (PRR), and 122 Hz sampling rate (SR). The resulting vertical standard error was 0.047 m and the average density of point cloud reached 5.1 points per m^2.

2.2. Ground calibration data

Ground calibration data were used for construction of diameter at breast height (DBH) models. A total of 1 372 trees with a DBH ≥ 7 cm within nine calibration plots covering a total area of 3.3 ha were assessed and measured for species, height, DBH, vitality, and social status. On the plots, a relevant ranges of slope gradients as well as of forest stands in different developmental stages and vertical structures were represented. Also a majority of tree species native to the region was present in the plots. The conifers were mostly composed of Norway spruce (*Picea abies* L. Karst) with 42% coverage, Silver fir (*Abies alba* Mill.) with 13% coverage, and European larch (*Larix decidua* Mill.) with 0.1% coverage. The broadleaves mostly consisted of European beech (*Fagus sylvatica* L.) with 34% coverage, Sessile oak (*Quercus petraea* Matusch) with 6% coverage, and European hornbeam (*Carpinus betulus* L.) with 3% coverage. The crown canopy closure in the plots ranged between 78 and 100%, and almost 75% of the measured trees were situated in the overstory.

2.3. Ground reference data

Ground reference data were used for validation of the method. These data were collected during the leaf-on season in 2013 from four reference stands with different types of species mixture (predominantly coniferous, predominantly broadleaved and mixed). These stands covered approximately 7.5 ha, and their borders were determined with GNSS measurements, resulting in a positional error of less than 1 m.

Variables from 2 203 measured trees with DBH ≥ 7 cm and heights ≥ 5 m were used for the purposes of

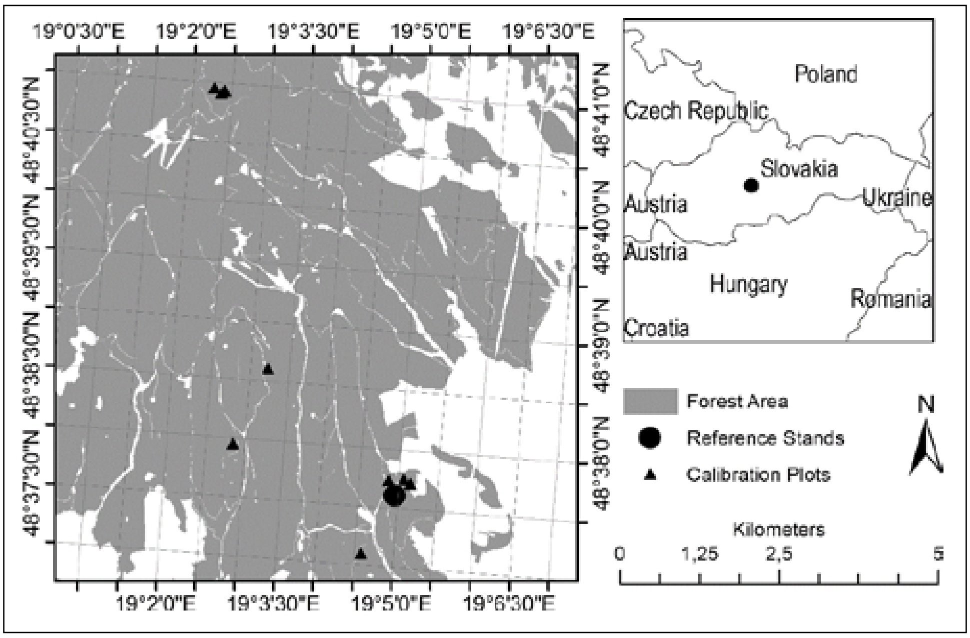

Fig. 1. Location of the study area, calibration plots, and reference stands.

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this study. A minimum tree height parameter was set to reflect the commonly accepted forest definition by FAO FRA (Food and Agriculture Organization of the United Nations, 2018). The quadratic mean diameter *(d_q)* was calculated based on *DBHs*, and the quadratic mean height *(h_{dq})* was calculated using a regression of d_q. The total volume *(V)* calculation was obtained by summing up the volumes of the measured trees. Here, the tree volume models introduced by Petráš et al. (1991) were used. An overview of the ground reference data is presented in Table 1.

Table 1. Ground reference data characteristics.

Stand	Group of Species	A [ha]	TPH	h_{dq} [m]	d_q [cm]	VPH [m^3 ha^{-1}]
C	Coniferous ≥ 70%	1.64	241	33.70	43.01	520.77
CB	Con./Broad. ≈ 60/40%	1.90	199	27.31	35.76	229.89
BC	Broad./Con. ≈ 60/40%	2.07	366	24.59	30.69	292.95
B	Broadleaved ≥ 70%	1.85	364	25.20	31.73	337.97

Note: A (ha): area in hectares; TPH: number of trees per hectare; hdq (m): regression height of the tree with the quadratic mean diameter in metres; dq (cm): quadratic mean diameter in centimetres; VPH (m^3 ha^{-1}): total volume per hectare in cubic metres.

2.4. Predicting forest stand variables from airborne LiDAR data

2.4.1. Individual tree and tree height detection

The treetops, tree crowns, and tree heights were detected using the reFLex algorithm (National Forest Centre, Zvolen, Slovakia). There, the initial procedures (i) divided the points into a three-dimensional regular mesh, (ii) calculated the absolute height above the ground for each point, and (iii) reduced the number of points in the input file by applying a minimum tree height threshold (5 m). These operations produced a point cloud that was further used in an iterative search for treetops and tree crowns by using a moving-window analysis. Since there is a reason to assume that a part of the local maxima identified in the previous operation may not indicate the real treetops, an additional geo-dendrometric (GD) test was applied. The GD test is linked to a priori information and includes two steps: (i) evaluation of height differences between the local maxima, and (ii) evaluation of horizontal and vertical distances between the local maxima. This way, the false treetops located in the crowns of other trees are removed. The final procedures were applied to delineate the tree crowns. After the treetop identification and crown delineation, tree heights were recorded and crown coverage was calculated. Finally, the outputs of all procedures were exported to point and polygon vector files in an ESRI shapefile format. All details of the algorithm are listed in the study of Sačkov et al. (2017).

2.4.2 Classification of tree species groups

The classification was carried out for two general groups of tree species: (i) broadleaves, and (ii) conifers. These groups were classified based on combination of intensity raster and canopy height model (CHM) with pixel size of 1.0 m. First, the range of spectral information in the form of the backscatter intensity of the laser signal for each group of species was identified through visual interpretation, and the intensity raster with pixels representing broadleaves, conifers, and ground was created. Second, pixels smaller than 5 m CHM height were removed from the intensity raster and, thus, the final intensity raster included only the broadleaved and coniferous group. Finally, one of the species groups was assigned to detected trees using zonal statistical functions.

2.4.3 Tree diameter derivation

The DBHs of the detected trees were derived based on nonlinear regression models. The model predictor was tree height for the selected group of tree species (*DBH = f(h)*). The calibration dataset included 769 broadleaved trees and 603 coniferous trees (Section 2.2). The statistical significance of models was assessed using the F-test at a significance level of $\alpha = 0.05$. We found the exponential function to be most suitable for DBH derivation. The average accuracy for these models was 19% at the tree level.

2.4.4 Tree volume derivation

The volume for detected trees was derived based on the models introduced by Petráš et al. (1991). For each remotely detected tree with estimated height, assigned tree species group, and derived DBH, the volume calculation was applied using the adopted model. We used beech function for trees assigned to the broadleaved group and spruce function for trees assigned to the coniferous group because these species achieved a highest proportion of the total volume within forest stands.

2.4.5 Stand variables calculation

With respect to selected criteria (Section 2.3), only detected trees higher than 5 m were used for the purposes of this study. The stand height and stand diameter were calculated as the average of the tree data. The total volume was calculated as a sum of the tree volumes.

2.5. Accuracy assessment

The accuracy of tree detection was assessed through extraction rate (ER) as the difference between total number of ALS-extracted trees and total number of ground-measured trees. Thus, the commission or omission error were not calculated directly. This is because we were particularly interested in evaluating the fully autonomous prediction of stand variables that is achievable

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without human intervention (e.g., application of positive or negative biases of tree detection methods). On the other hand, the under- or over-estimation of detection was indirectly assessed through the histogram of height intervals with relative frequencies of ALS-extracted trees and ground-measured trees.

The accuracy of estimations of stand height, stand diameter and total volume was carried out by comparing of ALS-predicted stand variables and ground-measured stand variables. The mean difference (e) was calculated as the average of individual differences and was used as an indicator of underestimation or overestimation. The random error component (se) was used to assess the dispersion of differences around the mean difference. The root mean square error (RMSE) was used to aggregate both the systematic and random error components. The resulting RMSE should indicate the range of total accuracy for the whole study area at the 68% confidence level. The relative e%, se%, and RMSE% were calculated as the ratios of their absolute values and the arithmetic average of the reference data. Finally, we used the Mann-Whitney U test to assess the significance of differences (i) between predicted variables within forest stands, and (ii) between predicted and measured stand variables within forest stands ($p < 0.05$). This non-parametric test was selected primarily because a normal distribution of mean differences was not confirmed within the dataset ($p < 0.05$).

3. Results

The extraction rates for the C, CB, BC, B stand were 63%, 76%, 57%, and 63%, respectively. Specifically, Fig. 2 shows the relative frequencies of ground-measured and ALS-extracted trees within height intervals. The average underestimation achieved the value of −9.7% and the extreme was found within the height interval of 20–25 m (−14%). The average overestimation achieved the value of 5.7% and the extreme was found within the height interval of 25–30 m (15%). The differences in extraction rates between strata were not significant, thus the effect of tree species composition was marginal in these cases ($p < 0.05$).

The RMSE did not exceed 1.9 m (7.2 %) for mean height, 3.03 cm (8.6 %) for mean diameter, and 12.88 $m^3 ha^{-1}$ (15.0 %) for total volume. The overview of all predictions and accuracies for all stands is presented in Fig. 3–5. The ALS-based predictions of all stand variables were statistically significantly different relative to the ground data ($p < 0.05$).

4. Discussion

In this study, we applied our own multisource-based method related to the ITD approach to estimate forest stand variables from airborne LiDAR data in Central Europe forests with several types of species mixture. Tree positions and tree heights were directly extracted from original point cloud. The DBHs and tree volumes were derived through allometric models. Finally, three main forest stand variables (i.e., mean height, mean diameter, and total volume) were calculated based on tree data.

A slightly higher accuracy of detection as well as prediction was achieved within stands, with substantial or moderate dominance of coniferous trees (C and CB).

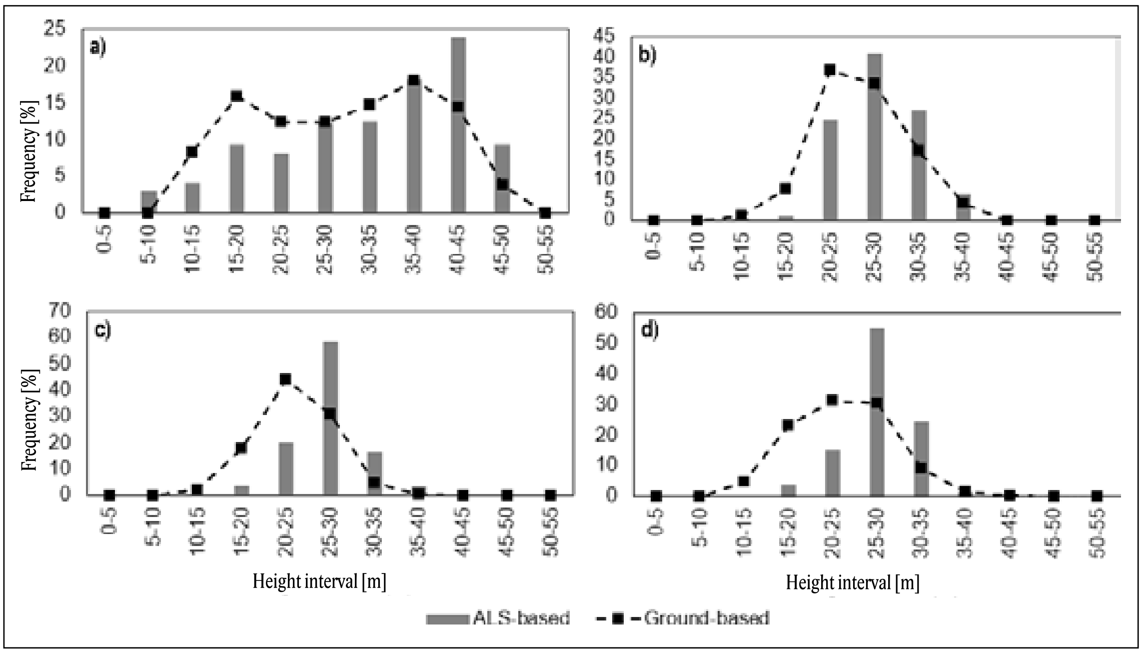

Fig. 2. Relative frequencies of ground-measured and ALS-extracted trees within height interval: (a) Coniferous stand, (b) Coniferous/Broadleaved stand, (c) Broadleaved/Coniferous stand, (d) Broadleaved stand.

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However, the statistically significant effect of tree species mixture on the overall accuracy was not confirmed in this study ($p < 0.05$).

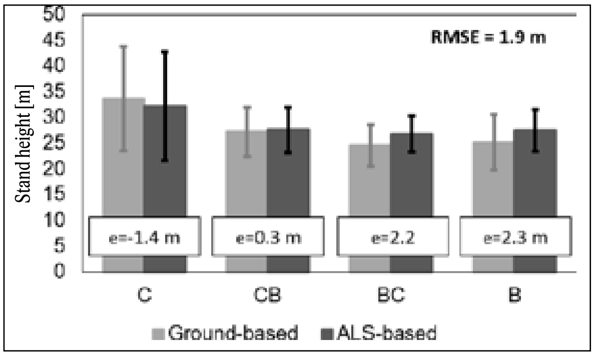

Fig. 3. Comparison of ground-measured and ALS-predicted stand heights.

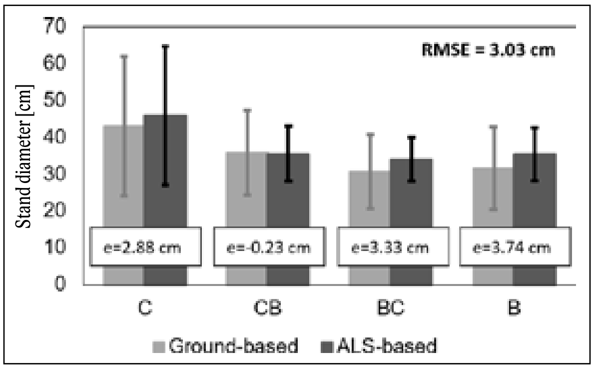

Fig. 4. Comparison of ground-measured and ALS-predicted stand diameters.

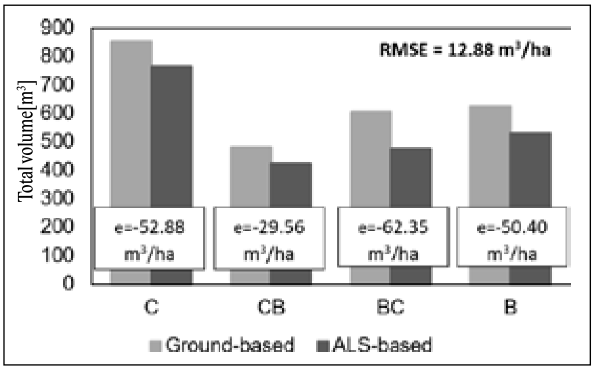

Fig. 5. Comparison of ground-measured and ALS-predicted total volumes.

The mean difference of ALS-predicted stand height ranged from −1.4 m to 2.3 m and decreased as all stand parameters increased. Using a similar approach and data format, Gaveau & Hill (2003) reported a mean difference that ranged from −0.91 m to −1.27 m for deciduous forest, while Sibona et al. (2017) achieved a mean difference of 0.95–1.13 m for coniferous forest. Chávez & Tullis (2013) evaluated stand height using ALS data and hyperspectral imagery over full-canopy oak-hickory forests with a mean difference of 1.67–2.99 m and RMSE of 2.1–3.7 m.

The accuracy of ALS-predicted stand diameters increased with increasing mean heights, however, with increasing total volume and stocking density, the accuracy decreased. Although the models used for DBH derivation in this study were relatively simple, the mean difference was comparable with other studies. For example, Yu et al. (2011) and Wu et al. (2015) reported accuracies that ranged from −17.6 cm to 13.2 cm in terms of mean difference. Moreover, other models for DBH derivation often used more variables than just tree height (e.g., crown area, crown length, crown volume).

Although all ALS-extracted trees were used for the stand volume prediction, the total volume was underestimated within all reference forest stands. The mean difference ranged from -29.56 m^3 ha^{-1} to -62.53 m^3 ha^{-1} and the accuracy increased as all stand parameters increased. There were three possible reasons for this. First, the omission error caused by undetected understory and suppressed trees, mostly resulting in underestimations of biophysical attributes when aggregated at the plot level. Second, the volume functions only for two species groups were used as a compromise. Finally, the density of ALS point cloud was relatively low for ITD approach. Despite these findings, our results were still within the range of achievable accuracy indicated by other studies. Kandare et al. (2017) reported the RMSE of 152.18 m^3 ha^{-1} and mean difference of 132.37 m^3 ha^{-1} using an ITD approach, the RMSE of 102.78 m^3 ha^{-1} and mean difference of –1.59 m^3 ha^{-1} using a semi-ITD approach, and the RMSE of 182.75 m^3 ha^{-1} and mean difference of −15.88 m^3 ha^{-1} using an area-based approach for heterogeneous forests in Italy. Ullah et al. (2016) achieved the RMSE of 66.31–66.67 m^3 ha^{-1} through multiple linear regression, k-Nearest Neighbour, and support vector machine for heterogeneous forest in Germany.

5. Conclusions

Results show that an author's method that is based on ITD approach can be used for predicting forest stand variables, such as stand height, stand diameter, and total volume. With respect to other studies, our findings also indicated that airborne LiDAR data are suitable mainly for the prediction of stand heights (Smreček et al. 2018). The method has been less successful for indirectly derived stand variables (e.g., stand diameter, total volume). However, the prediction of these variables typically depends on point density across a point cloud, input variables, and allometric models (Kamińska et al. 2019).

A significant improvement to the method would, therefore, be achieved mainly via using more complex techniques for tree species classification and more precise allometric models. Further research and development of reFLex algorithm is also needed to implement

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the presented approach into forest inventory practice in various ecosystems.

Acknowledgments

This research was supported by the Slovak Research and Development Agency in the framework of the project "Innovations in the forest inventories based on progressive technologies of remote sensing, ProMon" (APVV-15-0393) and by the Research and Development Operational Programme funded by the EU in the framework of the project "Using forest dynamics models for decision support systems, DYNAMO" (NFP313010T597).
Ivan Sačkov acknowledges the receipt of a fellowship from the OECD Co-operative Research Programme: Biological Resource Management for Sustainable Agricultural Systems in 2019.

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Cent. Eur. For. J. 65 (2019) 198–205 sciendo DOI: 10.2478/forj-2019-0021 CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

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The vertical accuracy of digital terrain models derived from the close-range photogrammetry point cloud using different methods of interpolation and resolutions

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Abstract

Structure-from-motion (SfM) in combination with multi-view stereo (MVS) represent techniques, which allow efficient generation of the point cloud from close-range photogrammetry (CRP) images of forest ground. Recent software products for the generation of digital terrain models (DTM) includes a wide range of interpolation methods. Previous studies showed different errors in elevations of DTMs interpolated with different methods. This study aims to analyze differences between the elevations of DTMs derived from CRP point cloud using different methods of interpolation. Six methods of interpolation included in modular system OPALS were tested in the study. In addition to simple methods of interpolation such as Snap or Moving average, more complex methods were used for interpolation of the DTMs elevations. For each method, 5 DTMs with resolution ranging from 1 to 20 cm were generated. Elevations of the DTMs were compared with the elevations of Global Navigation Satellite System (GNSS) surveyed check points. RMSE of DTMs elevations ranges from 3.4 cm to 16.2 cm. Differences between the elevations of DTMs interpolated using different methods and resolution were further investigated using one-way analysis of variance (ANOVA). The ANOVA rejected the statistical significance of the differences. Additionally, the spatial distribution of errors was analyzed. The analysis indicates that the interpolation of the extreme DTM values can be expected at the edges of the DTM when using the CRP images captured from single passing through the study site.

Key words: close-range photogrammetry; digital terrain model; OPALS; structure-from-motion; multi-view stereo

Editor: Vladimír Šebeň

1. Introduction

Monitoring of forest ground is very important, especially during the harvest. The monitoring can help prevent the negative impact of soil erosion on the forest. The impact of soil disturbances on the forest was demonstrated in many studies (Jacobsen & Greacen 1985; Heninger et al. 2002; Modrý et al. 2003; Bassett et al. 2005; Schäffer et al. 2012; Gebauer et al. 2012; Cambi et al. 2016). The disturbances affect mainly the root growth, which consequently decreases the forest regeneration (Heninger et al. 2002; Modrý et al. 2003; Bassett et al. 2005; Gebauer et al. 2012; Cambi et al. 2016). Moreover, the disturbed soil can also decrease water quality (Christopher & Visser 2008). Generally, the studies confirm the significance of the forest ground monitoring as a tool for avoiding further degeneration of forest growth and water quality (Christopher & Visser 2008; Schäffer et al. 2012; Affek et al. 2017).

Close-range photogrammetry (CRP) has already shown its potential to provide very detailed and accurate digital terrain model (DTM) (Zapp & Nearing 2005; Gessesse et al. 2010; Westoby et al. 2012; Liu & Huang 2016; Hrůza et al. 2018; Chudý et al. 2019). According to Pierzchała et al. (2015), the advantage of photogrammetry-based methods using modern compact cameras is that they can be used handheld or mounted on forest machines or low-cost drones, while laser scanners remain comparatively heavy and costly. Furthermore, using a handheld camera for image acquisition is the easiest and cheapest way to capture the state of the forest at a particular moment in time. DTM derived from CRP images taken from a close distance can dispose of sub-centimeter vertical accuracy (Zapp & Nearing 2005; Gessesse et al. 2010). However, these models are limited only for an experiment with area up to a few tens of square meters. Digital terrain models with larger areas dispose of lower accuracy and are usually derived from

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CRP images acquired in a kinematic manner (Hrůza et al. 2018; Chudý et al. 2019).

Structure-from-motion (SfM) and multi-view stereo (MVS) methods are used for the generation of the point cloud from CRP data. DTM can be derived using only the SfM-MVS software (Pierzchała et al. 2015; Goetz et al. 2018). DTM can also be derived from a point cloud generated by SfM-MVS software using additional software (Haas et al. 2016; Mölg & Bolch 2017). The vertical accuracy of DTM derived from CRP point cloud is influenced by multiple factors. The image matching precision can mainly be affected by choosing the optimal software for the point cloud generation. Some differences in vertical accuracy of DTM and quality of point cloud generated by different software were shown (Niederheiser et al. 2016; Mölg & Bolch 2017).

Evaluation of DEMs for skid trail erosion assessment was discussed in previous studies (Haas et al. 2016; Pierzchała et al. 2016). Quality of the digital elevation model (DEM) was assessed using yardstick measurements taken along the skid trail in Haas et al. (2016). DEM validation can be also carried out by manual measurements of skid trail profile as it was demonstrated in Pierzchała et al. (2016). However, in most of the studies, the vertical accuracy of DEM is assessed using the GNSS and total station surveyed check points (Arun 2013; Liu & Huang 2016; Goetz et al. 2018; Tomaštík et al. 2019). Laser scanning derived DEM can also be used as reference data for DEM vertical accuracy assessment (Westoby et al. 2012; Gašparović et al. 2017). The continuous data are very beneficial for the detection of bias of tested DEM.

Influence of interpolation method on the DTM quality has been investigated in previous studies (Robinson & Metternicht 2006; Arun 2013; Akar 2017). The method can influence DTM with lower resolution commonly derived from satellite imagery (Robinson & Metternicht 2006; Arun 2013). Differences between the high-resolution DTMs derived from UAV imagery interpolated using multiple methods has shown to be not significant (Akar 2017). Comparison of some studies also shows how much is the vertical accuracy of DTM influenced by its resolution (Robinson & Metternicht 2006; Arun 2013; Akar 2017).

Although the CRP point cloud usually disposes of high point density, factors such as DTM resolution and method of the DTM interpolation should be investigated. Latest software for DTM generation provides a wide range of interpolation methods (Robinson & Metternicht 2006; Mandlburger et al. 2009; Arun 2013). This study aims to analyze the vertical accuracy of DTM derived from CRP point clouds with respect to DTM resolution and interpolation method. Additionally, the study aims to analyze the spatial distribution of DTM errors to further reveal the cause of extreme value interpolation.

2. Materials and methods

2.1. Study site

This study was conducted for the skid trail located within the forest in Budča, near Zvolen in the Slovak Republic (Fig. 1). Study site covers approx. 1 022 m^2 of forest road and neighboring areas. The forest is managed by Forest enterprise of Technical University in Zvolen - Budča. Study site lies in the area with southeastern aspect and average slope of 35%.

Forest surrounding the study site began to be harvested a few months before the data acquisition. Studied skid trail begins at the logged part of forest stand and connects the forest with a highway. It directs from northwest to southeast. Harvesting was carried out in the southeastern part of the study area, which is situated at lower elevations compared to the skid trail. Studied part of the skid trail was not affected by the recent harvest.

2.2. Close-range photogrammetry survey

CRP images from 70 meters of the skid trail and surrounding areas were acquired. Data acquisition was done in late November 2017. Canon EOS 5D Mark II camera mounted on a pole was used for the image acqui-

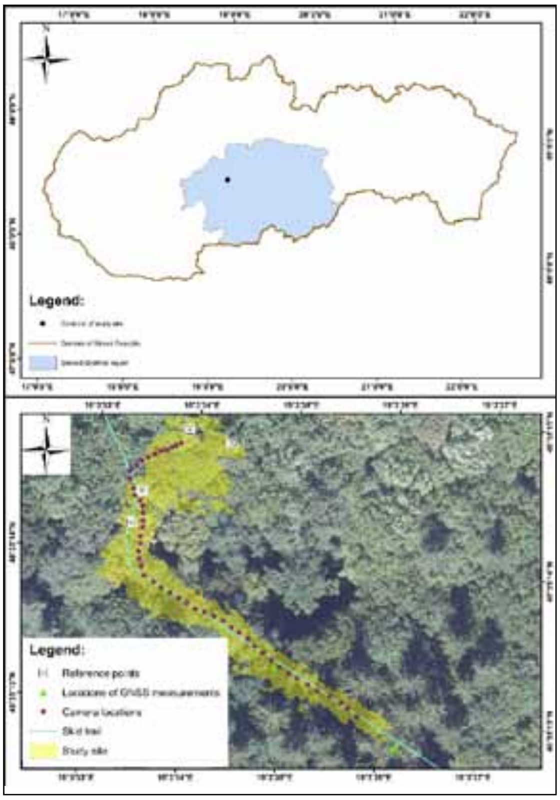

Fig. 1. Location of study site within the borders of Slovakia is shown in the upper figure. Locations of the camera during the CRP surveys, locations of static GNSS measurements and locations of reference points used for point cloud georeferencing are shown in the lower figure.

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Table 1. Camera specification.

Camera	Resolution	Focal Length [mm]	Pixel Size [µm]	Precalibrated
Canon EOS 5D Mark II	5616 × 3744	35	6.55 × 6.55	No

sition (Table 1). The camera was located 2.5 m above the ground during the acquisition. Eighty-eight images of forest ground were acquired with a shutter speed of 1/80 s, the f-number of f/6.3 and ISO of 400. In the first survey, 48 images were acquired with 4 reference points. In the second survey, 40 images were acquired with 5 reference points. The images were acquired by moving the camera along the centerline of the skid trail. Positions of the camera during the CRP surveys are shown in Fig. 1.

2.3. Static Global Navigation Satellite System and total station survey

Check points within the study area were surveyed using a total station and two static GNSS measurements (Fig. 1). The points were firstly surveyed by the total station and telescopic prism pole with a bubble. Tip of the pole was placed on the ground surface without inserting the pole into the soil. Locations of the 145 check points were measured. The points were surveyed from only one position of the total station. Coordinates of the points measured by the total station were transformed to S-JTSK coordinate system using two static GNSS measurements with 10 min duration. The static measurements were located at the edge of the recently harvested area (Fig. 1). Locations of GNSS measurements were checked using the total station. Distance from one point measured using GNSS to another was compared to the distance measured using the total station. If the difference between the distance measurements was higher than 2 cm, the GNSS measurement was carried out again.

The precision of static GNSS measurements was assessed by Slovak real-time positioning service (SKPOS). Horizontal precision was 0.4 cm and vertical precision was 0.6 cm for the point located inside the study site (Fig. 1). Horizontal precision was 0.8 cm and vertical precision was 1.4 cm for a point located outside the study site.

2.4. Close-range photogrammetry point cloud generation

CRP images were aligned and georeferenced in Agisoft's PhotoScan (Agisoft LLC 2016). Images alignment was set to the highest accuracy and pair selection was disabled. Images were aligned using 310,345 tie points for the first survey. Images from the second survey were aligned using 162,796 tie points. Point clouds were georeferenced using 4 and 5 control points. The precision of the georeferencing was calculated in PhotoScan based solely on the control points. For the first and second survey, the point cloud was georeferenced with XY RMSE of 0.22 cm and Z RMSE of 0.06 cm, XY RMSE of 0.9 cm and Z RMSE of 0.24 cm, respectively. This precision was considered as sufficient for the generation of DTM. Point clouds from 2 surveys were merged and new point cloud consisted of 65,402,845 points.

2.5. Ground points classification

Software suite – LAStools (Isenburg 2016) was used for classification of ground points. LAStools classifies the ground points using the triangulated irregular network (TIN). Four parameters are necessary for the classification. First, the size of the step used for classification was set to 1 m. Maximal bulging of the TIN was set to 1 m. Points located 0.3 m above the coarsest TIN were defined as the up-spikes and removed. Points located more than 3 m below the TIN were defined as down-spikes and removed. Points up to 5 cm above the TIN based ground were classified as the ground points. Finally, ground points were exported as a new point cloud with a density of 334 points/m^2. The point cloud was then used during the following processing.

2.6. Generation of digital terrain models

Ground points extracted from CRP point clouds were used for DTM generation. DTMs were generated in OPALS, version 2.3.0 (Mandlburger et al. 2009; Otepka et al. 2012; Pfeifer et al. 2014). The OPALS module Grid offers eight methods of grid interpolation as well as five methods of DTM gaps filling. Six methods of the interpolation (Snap, Delaunay triangulation, Moving average, Moving paraboloid, Moving planes, Robust Moving planes) were tested in this study.

In addition to simple methods of interpolation such as Snap or Moving average, more complex methods were used for interpolation of the DTMs. Delaunay triangulation uses the TIN for grid interpolation. To avoid data gaps for an interpolated grid cell, additional points from neighboring cells are considered within a distance of 3 times the grid cell size. The methods based on the moving plane (Moving planes, Robust Moving planes) use the plane tilted so it best fits the points within the DTM cell to interpolate the cell value. For each grid cell, 8 nearest points are queried and a best-fitting tilted plane is estimated (by minimizing the vertical distances) (OPALS Team 2016). The height of the resulting plane at the grid point (x, y) position is mapped to the grid cell. The tilted plane interpolator allows the derivation of slope measures (x–component of the surface normal unit vector, y–component of the surface normal unit vector, slope, exposition) for each grid point. Moving paraboloid searches

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for the paraboloid (2nd order polynomial) that best fits the points located within the cell of DTM to interpolate its value. The height of the resulting paraboloid at the grid point (x, y,) position is mapped to the grid cell (OPALS Team 2016). The paraboloid interpolator allows the derivation of curvature measures (minimum curvature, minimum curvature, mean curvature, Gaussian curvature) for each grid point. The more complex methods of interpolation can interpolate more accurate DTMs in certain cases. To test the methods for DTM generation from a very dense CRP point cloud, we compare the DTMs with the DTMs interpolated using simple methods such as Snap, for which the detail and accuracy are much more dependent on the quality of the source data.

For each method of interpolation, DTMs with resolution (grid cell size) ranging from 1 cm to 20 cm, with an interval of 5 cm were generated from a set of ground points. Apart from the DTM resolution and method of interpolation, all remaining parameters used for the generation of DTM were set to default.

In the next processing step, gap-filling module was used to generate compact DTMs without the gaps. The gaps are represented by pixels with NoData value within the DTM extent. Adaptive method of gap filling was used for processing of all the DTMs. The method uses adaptive plane fit with inverse distance weighting to interpolate missing values of the DTM grid cells. Boundary ratio was set to 1, so only gaps fully surrounded by data were filled.

Statistical significance of differences between reference elevations (static GNSS measurement) and elevation interpolated using all methods of interpolation was determined by one-way Analysis of Variance (ANOVA).

DTMs were validated in respect of vertical accuracy using check points from static GNSS and total station survey. Root mean square error (RMSE) and mean error (ME) were calculated for each DTM as it is defined in [2] and [3].

$$e = Z_{DTM} - Z_{DGNSS} \quad [1]$$

$$ME = \frac{\sum_{i=1}^{n}(e)}{n} \quad [2]$$

$$Z_{NDVI} = \frac{NDVI - \overline{NDVI}}{\sigma_{NDVI}} \quad [3]$$

where z_{DGNSS} is z coordinate of the check point measured by the GNSS and total station combination and z_{DTM} is the value of DTM cell, which center is the nearest to the check point. The possible bias of DTM interpolation was further investigated for DTMs with 1 cm resolution using the t-test.

For further analysis of the DTM, the spatial distribution of DTM elevation errors was investigated. Mean errors were calculated using errors of DTMs [Eq. 1] with the highest resolution (1 cm). Errors of DTM interpolated by Moving paraboloid were excluded from the calculation of the mean errors. These errors have significantly influenced the mean value because some extreme values were interpolated using this method.

3. Results

3.1. Digital Terrain Models

Overall, 30 DTMs were generated. For 145 regularly distributed check points, the elevation ranges from 359.88 to 366.14 m (Fig. 2). It can be seen that the mean elevation of DTMs with the resolution of 1 cm is slightly overestimated for all the DTMs (cross mark in Fig. 2). Furthermore, elevation ranges and standard deviation are shifted towards the higher values for all the DTMs. This indicates that the elevation values are positively biased. Besides this, the elevation values interpolated using different methods of interpolation are very similar. One-way ANOVA also rejected the statistical significance of elevation differences among the methods of interpolation and reference with a p–value of 1 for the DTMs with the resolution of 1 cm. The same result of ANOVA was achieved for DTMs with the resolution of 20 cm.

Root mean square error (RMSE) and mean error (ME) were used to validate each DTM in respect of vertical accuracy. Accuracies of the DTMs were assessed using 145 check points. For DTMs interpolated using

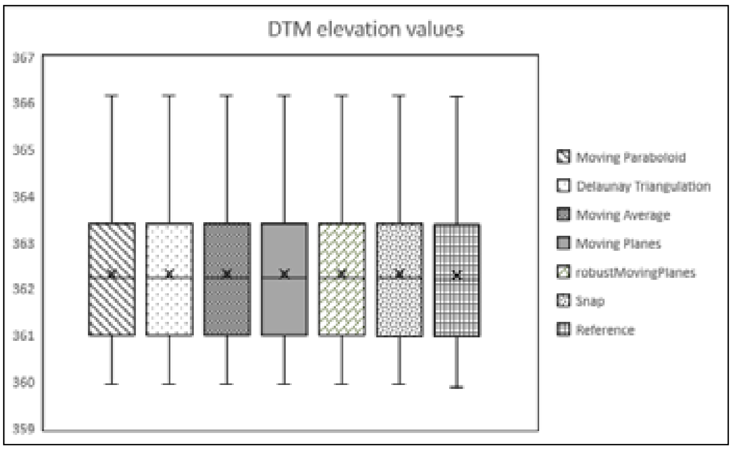

Fig. 2. Box plots of DTM elevation values for all DTM with a resolution of 1 cm.

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Robust moving planes and Moving planes methods, the number of check points varied between 143 and 145. The variability was caused by the different extent of DTMs with different resolutions.

For all the DTMs, mean errors were calculated. The errors show that elevations in the DTMs are overestimated with ME ranging from 1.19 cm to 2.39 cm (Table 2). The t-test rejected bias of the DTM elevations with very low p-values ranging from 1.51×10^{-18} to 9.33×10^{-6} (Table 2). Therefore, the slight positive bias visible on Fig. 2 is rejected.

RMSE was calculated for all DTMs. The error ranges from 3.4 cm to 16.2 cm. Highest RMSE was calculated for DTMs interpolated using Moving paraboloid method. Except for the DTMs interpolated using Moving paraboloid, the RMSE ranges only from 3.4 cm to 3.9 cm (Table 2). This result shows the small influence of method of DTM interpolation and DTM resolution on the vertical accuracy of DTM derived from CRP point cloud.

Furthermore, the spatial distribution of the errors was investigated. For 5 methods of interpolation (Moving Paraboloid excluded), the mean errors range from −5 cm to 8.79 cm (Fig. 3). Most of the errors are ranging from 3 cm to 4 cm (Fig. 3). Highest DTM errors are located at the edge of the DTM extent or in the areas with a higher occurrence of gaps derived from parts of the point cloud with lower point density (Fig. 4). The absolute difference between the lowest and highest errors is 8.78 cm. Most of the sub-centimeter errors are located near to the trajectory of images acquisition, in the areas with a low occurrence of gaps.

4. Discussion

Thirty different DTMs were interpolated from CRP point cloud of forest ground. The sample of elevations measured by static GNSS has a range of approx. 6 m. Statistical significance of differences interpolated using 6 different methods was rejected by one-way ANOVA. This was revealed for both 1 cm and 20 cm DTMs. Therefore, ANOVA rejected statistical significance also for the differences in elevation between the DTMs with different resolutions. Despite this, DTM vertical accuracy varies slightly. For all the DTM, positive mean error in elevation was calculated. In previous studies, the DTM elevations tended to be also underestimated (Hrůza et al. 2018).

Table 2. Mean errors and root mean square errors in DTM elevation for different methods of interpolation and DTM resolutions. Presented p-values for different methods of interpolation were calculated using t-test.

	Method of interpolation					
	Delaunay triangulation	Moving average	Moving planes	Moving paraboloid	Robust moving planes	Snap
DTM resolution [cm]	Root mean square error [cm]					
1	3.51	3.49	3.53	7.40	3.52	3.59
5	3.58	3.59	3.50	12.15	3.50	3.61
10	3.66	3.65	3.60	10.69	3.60	3.43
15	3.79	3.90	3.78	10.41	3.78	3.40
20	3.74	3.66	3.72	16.20	3.72	3.58
DTM resolution [cm]	Mean error [cm]					
1	2.21	2.25	2.65	2.27	2.27	2.22
5	2.30	2.32	1.58	2.26	2.27	1.95
10	2.39	2.38	1.42	2.35	2.35	1.89
15	2.29	2.32	1.80	2.28	2.27	1.33
20	2.31	2.28	1.76	2.22	2.22	1.19
p-value	1.94×10^{-17}	1.84×10^{-18}	9.33×10^{-6}	2.41×10^{-18}	1.51×10^{-18}	9.84×10^{-17}

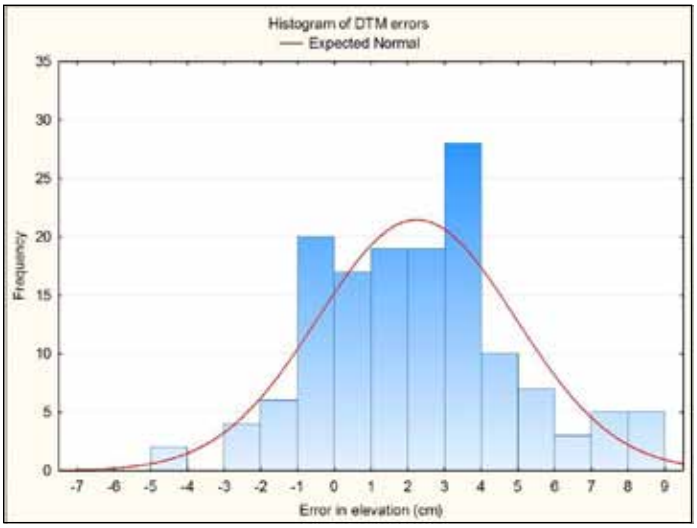

Fig. 3. Distribution of DTM errors. The errors were calculated as mean of errors of the DTMs with 1 cm resolution except for the DTM interpolated using Moving paraboloid method.

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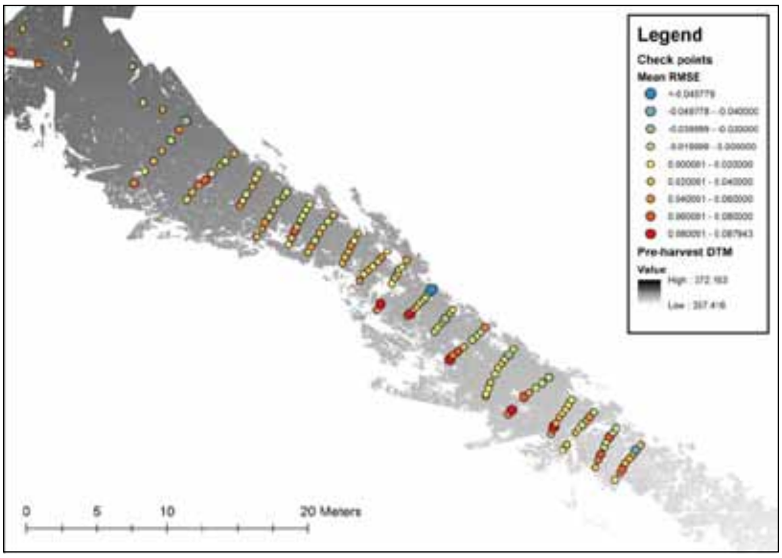

Fig. 4. Spatial distribution of errors with DTM in the background. The DTM with a resolution of 1 cm without filled gaps is shown in the figure.

The overestimation of elevations was reported for DTM derived from CRP images acquired statically (Gessesse et al. 2010). The overestimation is usually observed for DTM derived from airborne laser scanning data of forest ground (Reuterbuch et al. 2003; Sačkov & Kardoš 2014; Hrůza et al. 2018). Furthermore, the DTMs with overestimated elevations was reported for UAV-based photogrammetry point cloud (Goetz et al. 2018). Overall, the most accurate DTMs were interpolated using Snap method, which represents the simplest of all presented methods. Generally, the RMSE of DTM slightly varies around 3.5 cm, if we do not consider erroneous DTMs interpolated using Moving paraboloid method. DTMs with RMSE ranging from 1 to several meters are usually derived from satellite imagery (Arun 2013; Alganci et al. 2018). The errors of DTM derived from satellite imagery vary greatly also based on the land cover (Alganci et al. 2018). Lower accuracy can also be expected for DTMs derived from UAV imagery (Akar 2017; Goetz et al. 2018). The RMSE of DTMs derived from UAV imagery can reach approx. 5 cm (Goetz et al. 2018; Tomaštík et al. 2019). Very detailed DTMs can reach vertical accuracy up to several millimeters (Zapp & Nearing 2005; Gessesse et al. 2010). DEM with accuracy higher than the proposed DTMs can be derived from a point cloud generated from monochromatic images (Zapp & Nearing 2005). The standard error of elevation differences of 1.26 mm was reported by Zapp & Nearing (2005) for the experimental flume with dimensions of $4 \times 4 \times 0.8$ m^3. The similar standard error of ±5.6 mm was reported for DEM derived from CRP images of freshly tilled bare soil surface with plot size of 53 m^2 (Gessesse et al. 2010). Studies reporting very low standard errors were conducted for the study site with a small area and the CRP images were acquired in a static manner (Zapp & Nearing 2005; Gessesse et al. 2010). However, the studies show the highest vertical accuracy of DTM that can be achieved for the CRP data. Very promising accuracy (RMSE = 1.1 cm) was achieved also by Hrůza et al. (2018) for DTM from CRP point cloud of asphalt paved forest road. The CRP images were recorded from a car at the higher speed. On the other hand, the very smooth surface of the road causes an increase in vertical accuracy of the DTM.

Method of DTM interpolation influences the DTM vertical accuracy and the interpolated values can differ for surface models derived from airborne or satellite imagery (Arun 2013, Akar 2017, Alganci et al. 2018). For satellite imagery, the differences in interpolated values can reach several meters (Arun 2013). The differences in RMSE of DTMs interpolated using different methods can reach tens of centimeters even for photogrammetry point cloud from UAV (Akar 2017). Results of this study indicate a small influence of interpolation method on the vertical accuracy of DTM derived from CRP point cloud. Besides the Moving paraboloid method of interpolation, the DTM RMSE varies only a slightly for different methods of interpolation (0.5 cm). In this study, the DTM with extreme values was interpolated using Moving paraboloid method.

What seems to influence the vertical accuracy of DTM the most is the point cloud density. The spatial distribution of errors, shown in Fig. 4, shows that the highest errors are located either near the edges of the DTM extent or in areas with more gaps. These areas of DTM were interpolated from a smaller number of points. The errors of DTM values interpolated from low-density parts of the CRP point cloud can amount to 9 cm. For parts of the point cloud with a higher density of points, the DTM can be interpolated with an error of several millimeters. Besides the higher DTM error near the edges of DTM extent, for DTM of more complex terrain like mountains or rock glacier, the highest errors can be expected in areas with greatest elevation changes (Goetz et al. 2018).

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5. Conclusion

This study showed that the differences in elevation of DTMs interpolated using different methods of interpolation and different resolution of the DTM grid are not statistically significant. Except for the DTMs interpolated using Moving paraboloid, the RMSE ranges from 3.4 cm to 3.9 cm. Methods of interpolation presented in the study represent a wide range of approaches to the interpolation of DTM. Therefore, similar results can be expected for DTMs derived from CRP point cloud from forest ground interpolated using the method, which was not directly presented in the study. From the methods of interpolation presented in the study, we do not recommend the use of methods such as Moving paraboloid for interpolation of DTM from very dense CRP point cloud from the forest ground. Dozens of extreme values were interpolated using this method. Excluding the DTMs generated using Moving paraboloid, the mean RMSE decreases from 4.91 cm to 3.62 cm.

Spatial distribution of errors shows that the density of point cloud used for DTM generation can influence the vertical accuracy of DTM. Furthermore, the analysis of the spatial distribution indicates that the interpolation of extreme value can be expected at the edges of the DTM extent, which are located the farthest from the trajectory of image acquisition, especially in the case of using only single crossing through the study site for the acquisition. The density of point cloud is influenced mainly by the acquisition of CRP images and should be investigated in the future.

Acknowledgements

This study was supported by Science grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and Slovak Academy of Sciences project VEGA MŠ SR and SAV no. 1/0868/18: 'Innovative techniques for mapping anthropogenic and natural forms of terrain and relief applicable in survey of a landscape state'.

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Cent. Eur. For. J. 65 (2019) 206–217 sciendo DOI: 10.2478/forj-2019-0020

CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

http://www.nlcsk.sk/fj/

Suitability of MODIS-based NDVI index for forest monitoring and its seasonal applications in Central Europe

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Abstract

The paper demonstrates the multipurpose application of the normalized difference vegetation index (NDVI) derived from MODIS products for forest monitoring across the Central-European macro-region Slovakia and Hungary (i.e., the Western Carpathians and Pannonian basin). Relationships between forest dynamics and NDVI were analysed and used for determining the onset of phenophases in spring and autumn and for the assessment of forest growth and health condition. To identify the phenophases, the NDVI profile during the year was established by fitting a double logistic sigmoid function to data and phenological metrics were developed based on the calculated extreme values of the sigmoid function and its derivatives. According to our analyses, leaf unfolding and leaf fall were significantly delayed or advanced in 2018 with the increase of altitude and latitude ($p < 0.01$). The longitudinal aspect was significant only in the autumn phenophase with earlier onset of leaf fall towards to the east. The duration of the growing season varied extensively within the region, mainly according to altitudinal and latitudinal occurrence of beech forests. Positive associations between annual tree-ring width and standardized summer NDVI were found for conifers at local scale. The highest correlation period was between July 12 and August 12 as the most critical periods for forest growth. Slight positive correlation can be observed during March – April that could be associated with the varying start of the growing seasons. In the forest health study, whereas NDVI values could well identify the location and extent of a recent forest damage due to a combination of snow break and wind break, an urgent demand for more detailed field data was obvious.

Key words: MODIS; NDVI; forest phenology; growing season; tree ring; health condition

Editor: Michal Bošeľa

1. Introduction

Widespread abiotic and biotic disturbances started to occur with increasing frequency in Europe in the last decades (e.g. Lindner et al. 2014), including central European countries (Koltay 2006; Hirka 2018; Barka et al. 2018). The detoriation of forest health condition due to climate change and their possible adverse consequences in Central Europe (e.g. Somogyi 2016) are among the drivers in the development of remote-sensing based forest monitoring systems in this region.

Forest condition and plant phenology estimation over continuous spatial and temporal domains are essential for quantifying climate change impacts on forests and for understanding of vulnerability of forest ecosystems and socio-economic systems. Monitoring and research programs using such estimation are also the basis for suggestions of possible adaptation measures (e.g. Kovats et al. 2014). Satellite remote sensing seems to be an effective tool for this type of research. The advantages of using satellite sensors are the large spatial extent and high frequency of data collection, usually complemented with higher spectral resolution when compared with airborne sensors. Moreover, open access to satellite data with moderate or high resolution greatly increased their usage (Wulder et al. 2012), including forestry monitoring.

The conditions for monitoring forest health and phenology noticeably improved after the launch of the Terra and Aqua satellites (NASA Earth Observation System Satellites), equipped with the MODIS spectroradiometer (Moderate Resolution Imaging Spectroradiometer). The instrument collects data in 36 spectral bands, with wavelength ranging from 400 to 1 450 nm, at spatial resolutions from 250 m to 1 000 m (Justice et al. 2002). The most frequently used vegetation indices (i.e., the combi-

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nation of spectral values of two or more bands designed to enhance the contribution of vegetation properties) are the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI), especially in broadleaf forests (e.g. Beck et al. 2006; Heumann et al. 2007; Soudami et al. 2008; Hmimina et al. 2013).

Due to their moderate spatial resolution, it was questionable whether the MODIS data products could be used for forest monitoring at regional or even local scales. However, several studies from Central Europe exist which successfully utilize MODIS data for detection of stand-level intraseasonal climatic stress (Hlásny et al. 2015), forest damage (Bartold 2012) or continuous monitoring (Somogyi et al. 2018). This latter system (called TEMRE in Hungarian) was implemented for observing forest vitality related to environmental changes and describes forest health state by a standardized NDVI which is a measure of the intensity of photosynthetic activity, relative to a long-term local average.

Another possibility of using MODIS data for forest monitoring is to analyse the MODIS-based NDVI in combination with tree-ring chronologies. Tree-ring width is a widely used proxy for tree vitality (Fritts et al. 1971), and its relations to climate and extreme events, such as drought, are well recognized (Dobbertin 2005). The phenomena was studied in the south-western part of Hungary (Móricz et al. 2018) where the stands of Black pine (*P. nigra* Arn. var. *austriaca*) suffered from extreme droughts during the last decades. This latter study has found that the observed NDVI anomalies were in rough coincidence with remarkable growth reductions of trees due to drought conditions. However, no robust conclusions could be drawn due to the scarce availability of surface reflectance images of Landsat.

The seasonal variability of vegetation indices is related to phenology. Several approaches are available for modelling such variability, e.g. piecewise logistic functions (Ganguly et al. 2010), an adaptive Savitzky-Golay filter, asymmetric Gaussians function (Eklundh & Jönsson 2015), double logistic sigmoidal function (Fisher & Mustard 2007; Soudami et al. 2008) and its modification (Hmimina et al. 2013). During the last decade, phenology dynamics were analysed at pan-European level or at the level of European climatic zones (Delpierre et al. 2009; Hamunyela et al. 2013; Fu et al. 2014; Garonna et al. 2014; Jin et al. 2019). The research studies confirmed a general trend of extension of season duration due to its earlier onset and later end, although extensive variations in this trend were observed within and between climatic zones and landscape types.

Clearly, a more detailed macro-regional research is needed for a better understanding of how forests respond to changing environmental conditions. The main aim of this paper is to verify the applicability of MODIS-based NDVI for the detection and description of forest dynamics and forest conditions in Central European Region on the example of Slovakia and Hungary. The paper presents an analysis of the relationship between tree-ring chronologies and NDVI, field-based data on forest damages with NDVI in Bükk Mountains (Hungary), and the phenophases of beech stands based on the respective NDVI profiles for macro-region of the Carpathian Mountains and the Pannonia lowland for the year 2018.

2. Materials

2.1. Study area

The research was conducted within forests dominated by European beech (*Fagus sylvatica* L.) in Slovakia and Hungary. For the analysis of the phenological aspect, the minimum proportion of beech within the 250 × 250 m MODIS pixels was 50%. The total number of analysed pixels was 33 513, covering an area of 209 456 ha (Fig. 1A). Most of the beech stands extend between 200 and 1 100 m a. s. l. with average of 517 m.

Tree-ring analysis was done using samples from the Keszthely Mountains in south-western Hungary (46.83° N, 17.35° E, 200–400 m a. s. l. Fig. 1B). The spatial distribution of Black pine stands showed great similarity in growing and stand conditions such as shallow rocky soils with relatively little available water storage capacity and high crown closure.

The comparison of the MODIS-based assessment of forest health state with terrestrial observations was conducted in the Bükk Mountains in North-East of Hungary (Fig. 1C). In this region, a significant snow break, associated with a wind-fall and wind break events, caused forest damages on 4 409 ha of forests in April 2017 (Hirka 2018). The area is dominated by European beech (*Fagus sylvatica* L.) and Sessile oak (*Quercus petraea* (Matt.) Liebl.). The area has a cool and humid climate with average annual temperature below 8 °C, average precipitation 700 – 800 mm per year, typical soil types Luvisols, Cambisols and Rendzinas, and thickness rooting depth of more than 60 cm.

2.2. MODIS data

The phenological study was based on the MOD09 and MYD09 products (collection 6, United State Geological Survey, URL: http://e4ftl01.cr.usgs.gov). The MOD/MYD09GQ spectral bands 1 and 2 (centered at 648 nm and 848 nm) were used to derive the vegetation index NDVI at 250 m resolution. The *1km Reflectance Data State QA* layer from MOD/MYD09GA products was used for describing the quality of the products, particularly for cloud cover masking. Despite the potentially adverse effect of anisotropic reflectance of the vegetation on the use of MODIS daily products (Ju et al. 2011), we used the MOD/MYD09 because of spatial resolution and the necessity to capture immediate vegetation dynamics. Franch et al. (2013) claim that the effect of surface

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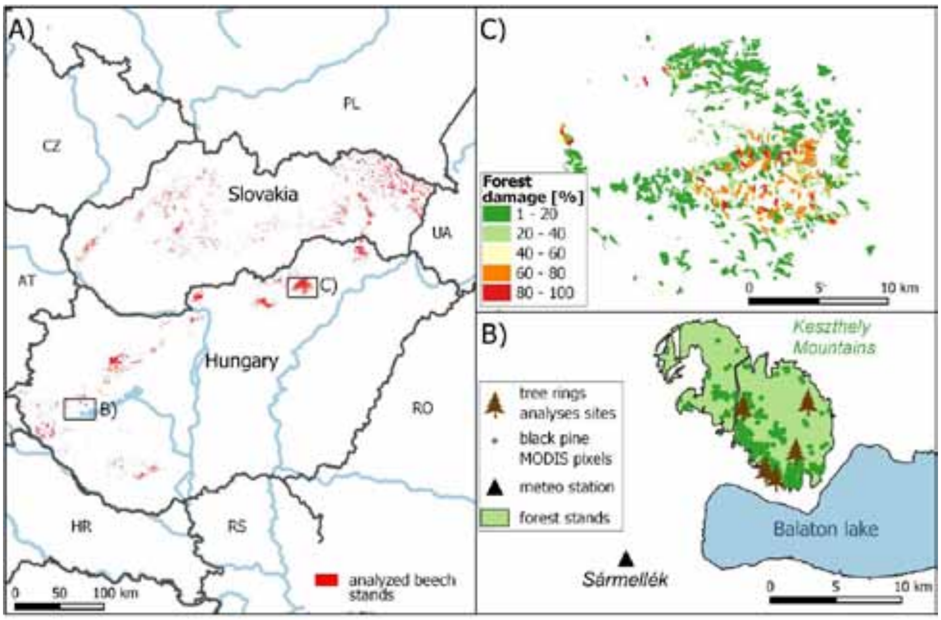

Fig. 1. A) The distribution of beech dominated pixels across Slovakia and Hungary. B) Study site in the Keszthely Mountains for a comparison of climatic indices and radial increment with the NDVI values. C) Study site in the Bükk Mountains for a comparison of field-based forest health assessment with the NDVI values; a map of the field-based forest damage frequency in 2017.

anisotropy in the red and infrared band of MODIS data barely influence NDVI estimation, obtaining RMSE of around 1%.

The TEMRE system is based on the MOD13Q1 – MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN grid product (downloaded from the same URL as above), which is a 16-day NDVI composite. In the case of the tree-ring study, MODIS NDVI pixels were filtered from TEMRE (in total, 217 pixels) for correlation analysis that were covered dominantly (> 50%) by Black pine forests with age between 30 and 60 years and shallow soil depth (< 60 cm).

2.3. Meteorological data

Daily meteorological data (temperature, precipitation) were used in tree-ring analyses. Data were obtained for the period 1999 – 2016 from the nearest Keszthely (Sármellék) station (Hungarian Meteorological Service), located about 10 – 15 km from the study sites (Fig. 1B). The standardized precipitation index (SPI) and the standardized precipitation–evapotranspiration index (SPEI) were calculated on the monthly scale that was averaged to seasonal scale for correlation with growth (Vicente-Serrano et al. 2010). SPI is based solely on long-term precipitation data while SPEI is a multi-scalar drought index that allows the monitoring of water availability over various timescales using the monthly difference of precipitation and potential evapotranspiration. Both drought indices were computed using the SPEI package of the R software.

2.4. Tree ring chronologies

Tree-ring-width chronologies were established at the five selected sites in the Keszthely Mountains, considered representative for the region (Fig. 1B, Móricz et al. 2018). At each site, 12 living dominant Black pine trees were cored at 1.3 m height using a Pressler increment borer (Haglöf, Långsele, Sweden). Since we were interested in the mean chronology of the sites, a single core per tree was considered representative of that tree for dendrochronological analyses. Tree-ring widths were measured on scanned images (1 200 dpi) in WinDENDRO environment (Regent Instruments, Canada) with a resolution of 0.001 mm. Cross-dating was statistically checked using the program COFECHA (Holmes 1983). To remove age-related growth trends each cross-dated ring width series was detrended with a negative exponential curve (Fritts 1976) using the program ARSTAN (Cook 1985). With regard to the modest autocorrelation checked by the Akaike criterion (AIC), a standard version of chronologies was calculated as bi-weight robust mean of the individual series. The signal strength of the index series was checked using the expressed population signal (EPS) statistics (Wigley 1984).

The high correlations (0.78 – 0.90) of standardized chronologies among the sites allowed using the mean chronology of the five sites (46 – 60 trees in total, depending on the number of available trees) to calculate correlations with climate indicators and NDVI.

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2.5 Field forest damage data

As field-based reference for forest damages (Fig. 1C), data from the Hungarian National Forest Damage Registration System (Nébih 2018) was used. This system is run by the NFCSO Forestry Department and the NARIC Hungarian Forest Research Institute. In total, 4 409.11 hectares of stands with various degrees of late frost damage were registered in 1 090 forest sub-compartments. The average damage, measured by the number of affected trees in percent of all trees, was 26.5% (Nébih, 2018).

3. Methods

3.1. Phenology analysis

3.1.1. MODIS quality analysis for phenological research

The quality of downloaded MOD09/MYD09 images was evaluated on image-level and pixel-level. The value of the spectral reflectance of each pixel is partly influenced by the spectral properties of the adjacent pixels (Townshend et al. 2000). This may increase the variability of the reflectance values. The pixels on the boundary between forest stands and other land cover classes were excluded from the analyses in order to minimize the variability of reflectance values.

Another criterion for the selection of appropriate images was the satellite position in relation to Slovakia and Hungary during data collection. Since the MODIS tracks are stable with 16-day repetitions, we could identify that there are 6 images in-nadir position related to Slovakia; 4 images in close-to-nadir position and 6 images in off-nadir position. Off-nadir images were completely excluded from downloading. Thus, we reduced the effect of anisotropic reflectance and achieved the spatial resolution close to 250 m. As the viewing angle increases, the actual ground pixel size increases continuously off-nadir both in along-track and along-scan directions (Kristof & Pataki 2009).

In addition to the visual inspection of image quality, we analysed the *1km Reflectance Data State QA* layer present in the MOD09GA/MYD09GA products. The quality information of individual pixels is encoded as values of individual bits in 16-bit integers. MOD/MYD09 product quality description and an optimal combination of bit values were applied in deciding on the inclusion or exclusion of a pixel in the analysis. Based on the data from the quality dataset, we selected pixels with the following bit values: 8, 72, 76, 136, 140, 200 and 8200. Other pixel values were treated as no data. This ensured that only the best quality data, not influenced by detected cirrus clouds, clouds, cloud shadows, snow or fires, were analysed.

Reflectance values (i.e., DN values) of the selected pixels underwent a final quality check. The arithmetic mean (x) and standard deviation (SD) of DN values were calculated for each selected image from the database. A pixel was included in the analysis if its value ranged within x ± 2 SD. The pixels outside this range were assigned a bit value of zero.

After applying the rules for image and pixel selection, the 68 images of the MODIS images were used for the analyses in year 2018.

3.1.2. Constructing a phenological model

Modelling phenology entails predicting the onset of the main phenological events through the analysis of NDVI during the year. The raw NDVI data were smoothed with sigmoidal logistic curve (Fisher & Mustard 2007) using the PhenoProfile software (Bucha & Koreň 2014):

$$v(t) = v_{min} + v_{amp}\left(\frac{1}{1+e^{m_1-m_2t}} - \frac{1}{1+e^{m_3-m_4t}}\right) \qquad [1]$$

Where $v(t)$ is NDVI observed at day of year (DOY) t; v_{min} and v_{amp} parameters correspond to the minimum value of the vegetation index (NDVI) and amplitude (maximum minus minimum); m_1 and m_2 parameters control the shape and slope of the curve of the ascending (spring) phase, and m_3 and m_4 parameters control the descending (autumn) phase.

In this study, v_{min} and v_{amp} parameters were not subject to formula [1] calculation, but they were used as constants. We used the values for beech: $v_{min} = 0.429$ and $v_{amp} = 0.497$ for spring phase and $v_{min} = 0.499$ and $v_{amp} = 0.417$ for autumn phase. The v_{min} and v_{amp} parameters for the spring phase have been taken from Bucha & Koreň (2014). There were 27 images from the spring period (DOY 92 to 181) used as an input in derivation of these 4 parameters. The autumn phase v_{min} and v_{amp} values were derived iteratively based on the minimum RMS error of equation [1]. The baseline values were identical to those of the spring phase. The values of v_{min} was gradually increased and v_{amp} decreased in steps of 0.01. The input set for autumn phenophase consisted of 37 images from the summer and autumn periods (DOY 181 to 321).

Calculation of $m_1 - m_4$ parameters was done separately for each pixel with beech occurrence. The extremes of the first and second derivatives of the function [1] were used to determine the approximative onset of the new phenological phase.

The period of the maximal rate of change corresponds with the inflection point (IP) in spring or autumn phenological phases (Fig. 2, Table 1). Other significant points of the function represent the days of maximal acceleration and maximal deceleration in spring and autumn phases, and these correspond to the local extremes of the second derivative of the sigmoid function.

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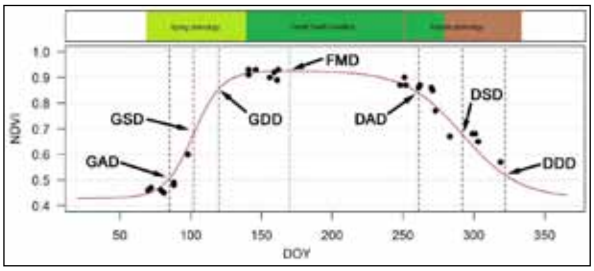

Fig. 2. The typical course of NDVI values of beech stands (dots) modelled by the sigmoid logistic curve [1] with the onsets of phenophases. Explanation of phenological metrics is given in Table 1.

Table 1. Satellite-derived phenological metrics based on the sigmoidal logistic curve and corresponding approximative vegetative phenophase.

GAD	Maximum (maximum acceleration) of the second derivative of the function in the spring phase ~ bud break onset
GSD	Extreme of the first derivative of the function in the spring phase (spring inflection point) ~ leaf unfolding onset
GDD	Minimum (maximum deceleration) of the second derivative of the function in a spring phase ~ end of leaf unfolding
FMD	Maximum of a phenological curve ~ Full foliage
DAD	Maximum (maximum acceleration) of the second derivative of the function in an autumn phase ~ leaf yellowing onset
DSD	Extreme of the first derivative of the function in an autumn phase (autumn inflection point) ~ leaf fall onset
DDD	Minimum (maximum deceleration) of the second derivative of the function in the autumn phase ~ the end of leaf fall

3.1.3. Statistical evaluation of phenological data

The onset of the main phenophases in beech stands was expressed by median values of the day of the onset for year 2018. Intra-annual variation was expressed by the 5 – 95% quantile.

Multiple linear regression analyses were applied in analysing spatial variation of GSD (DSD) in 2018 as the function of altitude, latitude and longitude.

Based on previous studies (Pavlendová & Snopková 2014), the thresholds for SOS and EOS (start and end of growing season) were set to GSD and DSD. The duration of the growing season (GS) was then calculated for each pixel as the difference between the day of the onset of leaf fall and the onset of leaf unfolding, i.e. GS = DSD − GSD.

3.2. Comparison of climatic indices and radial increment with the NDVI values

Correlation of the standardized NDVI at fine (250 m) spatial resolutions with two climatic indices was analysed and compared with the ring width time-series for different timescales of NDVI for the period 2000 – 2016. To assess the relationships among climate, tree growth and NDVI, Pearson correlations were used. Seasonal (3-months) averages of the SPI and SPEI were correlated with the standardized mean NDVI of the summer months (June – August) from spring of the previous year until summer of the actual year of ring formation. Correlation between the standardized tree ring chronology and standardized NDVI were calculated for each 16-day period of image acquisition (in total 23 during the year) over each mean standardized NDVI of the preceding 23 cycles of 16-day periods.

3.3. Forest health assessment

3.3.1. Construction of a model for forest health assessment with the NDVI values

Since the absolute values of the photosynthetic activity depend heavily on the seasonality and many other factors, standardized NDVI values were calculated that are much better for detecting health anomalies in time and space. For the mean date of any 16-day period, this standardized NDVI, Z_{NDVI}, is calculated the following way (Peters et al. 2002):

$$Z_{NDVI} = \frac{NDVI - \overline{NDVI}}{\sigma_{NDVI}} \quad [2]$$

where $\overline{NDVI}$ is the mean NDVI, and σ_{NDVI} is the standard deviation of NDVI values calculated from all the NDVI values of the entire 2000 – 2018 time series for the given date. Using the Z_{NDVI} values, the forest health state is classified in TEMRE using codes according to the anomaly from the mean : < −2 (possible serious vitality problem); −2 – −1 (possible moderate vitality problem); −1 – 0 (possible slight vitality problem); 0 – +1 (slightly better than normal state); > +1 (moderately better than normal state). Below zero Z_{NDVI} values, i.e. where the actual NDVI value is less than the long-term average, might indicate a forest health issue predominantly in larger blocks of forests if the anomaly lasts for a longer period.

In the forest health study based on the TEMRE system, the 16-day standardized NDVI layers from April to October (i.e., DOY 129 to 273) in the year of the damage 2017 and in the subsequent year 2018 were used. Maps from July 2015 and 2016 served as a reference for healthy forest state.

For tree-ring analyses, the 16-day periods with more than half of the pixels missing were (mainly in the winter seasons). Additionally, a manual quality control procedure was applied, aimed at removing NDVI values that were inconsistent with the expected annual NDVI cycle (Bruce et al. 2006). Finally, the missing data were linearly interpolated using the zoo package of the R software and the corresponding standardized NDVI values were calculated with the same procedure as used in the TEMRE system.

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3.3.2. Comparison of field-based forest health assessment with the NDVI values

Forest damage data of the sub-compartments were aligned with the corresponding MODIS pixels by selecting the sub-compartment with the greatest spatial extent under the pixels. The standardized NDVI values were acquired from the images and the resulting dataset was further statistically analysed in MS Excel software from the viewpoint of damaged area distribution within standardized NDVI values.

4. Results

4.1. Phenological research – a leaf unfolding and leaf fall phenophase

The overview of the onsets of spring and autumn phenophases of beech stands in 2018 is given in Table 2.

Table 2. The onsets of spring and autumn phenophases of beech stands in 2018 (DOY).

	GAD	GSD	GDD	DAD	DSD	DDD
Mean	101.6	107.7	113.8	273.3	285.2	297.1
Std deviation	2.8	2.8	4.1	4.0	4.7	8.5
Median	102	108	113	274	284	294
5% quantile	97	104	109	266	280	287
95% quantile	106	113	122	278	295	314
Duration	9	9	9	12	15	27

The average of the onset of leaf-unfolding in 2018 was DOY 108, expressed as median value. The duration of the GSD phenophase occurred in 2018, lasting 9 days from DOY 97 to 106. The average onset of leaf-fall in 2018 was DOY 284. The duration of the leaf fall phenophase was 15 days from DOY 280 to 295.

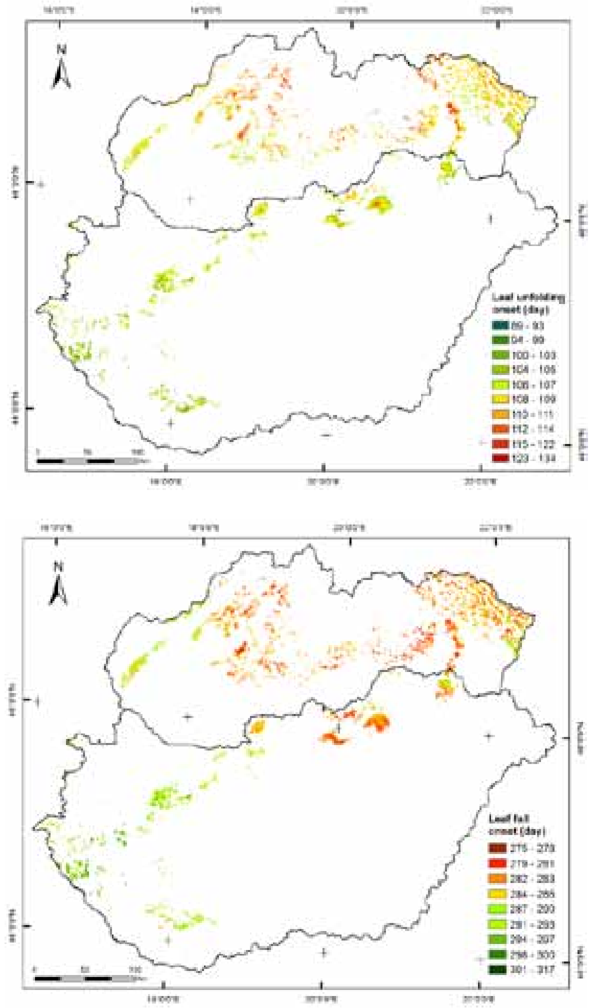

Fig. 3. GSD (left) and DSD (right) – DOY of the onset of leaf-unfolding and leaf-fall in 2018.

4.2. Temporal and spatial aspects of the onset of phenophases

The maps graphically depicting the spatial-temporal variation of the beginning of leaf unfolding and leaf fall of beech stands in macro-region Slovakia and Hungary, expressed as GSD and DSD, are presented in Fig. 3. The duration of the growing season is illustrated in Fig. 4. To enhance the visual perception, a median filter with the dimensions of 3 × 3 pixels magnified the number of pixels in all figures. The mean duration of the growing season (GS) for the whole macro-region was 177.6 days with standard deviation ± 6.66 days. The median value was 176 days and the duration of GS varied from 165 to 196 days (range 31 days), expressed as the 1 – 99th percentile.

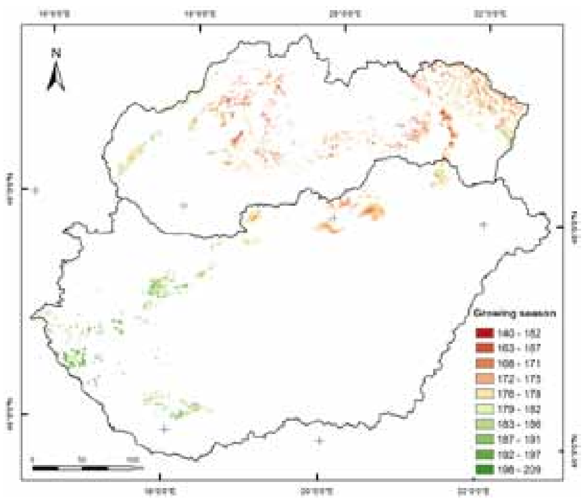

Fig. 4. Duration of the growing season 2018 in days: GS = DSD – GSD.

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4.3. Altitudinal and geographical aspects of the onset of phenophases

The results of multiple and simple regression analysis between the onset of GSD, DSD and the altitude and latitude and longitude are given in Table 3.

Table 3. Regression equations and correlation for GSD and DSD.

Multiple linear regressions:
GSD = 100.62 + 0.0082 * Altitude + 0.0026 * Latitude r = 0.74; Std. Error of estimate (SEE) = 1.91; p < 0.01; n = 32 610
DSD = 296.04 – 0.0079 * Altitude – 0.0029 * Latitude – 0.0030 * Longitude r = 0.71; Std. Error of estimate (SEE) = 3.28; p < 0.01; n = 32 610
Simple linear regressions:
GSD = 102.31 + 0.0107 * Altitude r = 0.67; Std. Error of estimate (SEE) = 2.09; p < 0.01; n = 32 610
GSD = 102.78 + 0.0046 * Latitude r = 0.57; Std. Error of estimate (SEE) = 2.31; p < 0.01; n = 32 610
GSD = 105.65 + 0.0018 * Longitude r = 0.36; Std. Error of estimate (SEE) = 2.63; p < 0.01; n = 32 610
DSD = 291.55 – 0.0123 * Altitude r = −0.49; Std. Error of estimate (SEE) = 4.05; p < 0.01; n = 32 610
DSD = 294.14 – 0.0080 * Latitude r = −0.62; Std. Error of estimate (SEE) = 3.64; p < 0.01; n = 32 610
DSD = 290.80 – 0.0048 * Longitude r = −0.59; Std. Error of estimate (SEE) = 3.74; p < 0.01; n = 32 610

Remarks: onsets of GSD and DSD are expressed in DOY (day of year); Altitude is expressed in meters above sea level. Latitude and Longitude are expressed in pixel order from 1 to 1 786 resp. from 1 to 2 151. One pixel represent dimension 250 × 250 m.

Concerning GSD, our analysis revealed a statistically significant correlation (r = 0.74; p < 0.01) between the onset of GSD (leaf unfolding) and the altitude and latitude. The estimated latitudinal shift (delay in onset) was 1.05 day per 100 km to the North, at a steady altitudinal shift of 0.82 day per 100 m. The longitudinal shifts was not significant (p > 0.05).

Concerning DSD, the analysis revealed a statistically significant (r = 0.71; p < 0.01) earlier leaf fall onset with altitude, latitude, and longitude. The estimated latitudinal shift was –1.17 day per 100 km to the North (early onset), whereas the longitudinal shift was approximately −1.20 day per 100 km to the East at a steady altitudinal shift of −0.79 day per 100 m.

4.4. Radial increment and climate indices vs NDVI values

The quality-checked NDVI time series showed a clear seasonal fluctuation for the selected Black pine sites with a slight but not significant decreasing trend (*Mann-Kendall tau = −0.0344, p = 0.286*) (Fig. 5A). The derived standardized NDVI is more informative for detecting NDVI anomalies such as the long and deep negative period after the drought event in 2011 – 2012 (Fig. 5B).

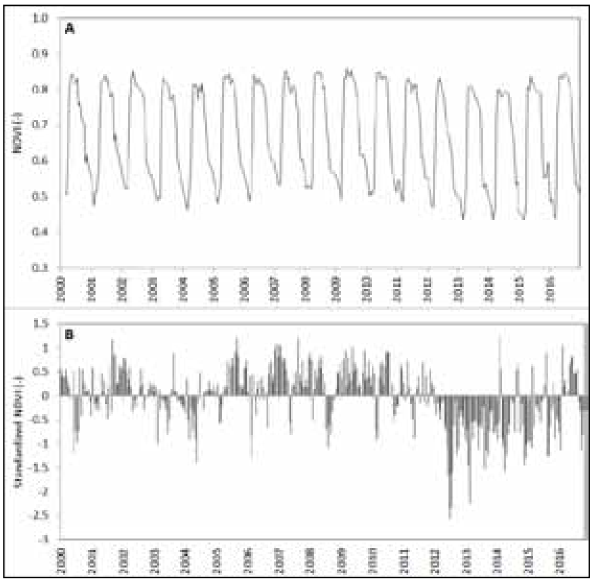

Fig. 5. Time series of row NDVI (A) and standardized NDVI (B) for the period 2000 – 2016.

The correlation between the mean summer standardized NDVI and corresponding seasonal drought indices was highest (r = 0.56 and 0.55) and significant (p < 0.05 one-tailed t test) with the current summer SPI and SPEI values respectively (Fig. 6.). The mean of spring and summer SPI and SPEI value also showed significant correlation with NDVI (r = 0.5 and 0.53, p < 0.05 one-tailed t test). Both drought indices demonstrate that precipitation was a good indicator of NDVI anomalies.

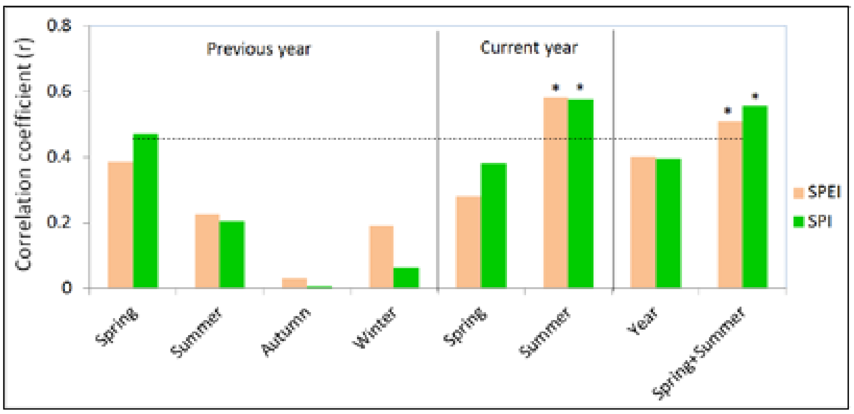

Fig. 6. Correlation between the mean summer standardized NDVI and corresponding seasonal drought indices.

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The NDVI from the beginning of June until the end of August (periods 11 – 15) and cumulating up to period 15 showed positive relationships with the corresponding annual tree-ring widths (Fig. 7).

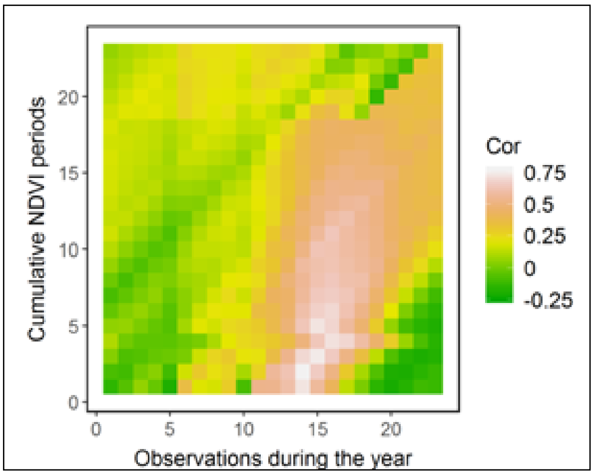

Fig. 7. Pearson correlation coefficients between time series of tree-ring width index and NDVI for different temporal scale (y–axis). The x–axis shows the 23 periods of the 16-day MODIS composites during a year.

The highest correlation period (r = 0.77) was between July 12 and August 12 as the most critical periods for forest growth. Slight positive correlation (r up to 0.36) can be observed during March-April that could be associated with the varying start of the growing seasons.

4.5. Field-based assessment of forest health vs NDVI values

The standardized NDVI of the area showed that forest vitality declined remarkably from the preceding years 2015 – 2016 to 2017, i.e., after the snow break occurred. The substantially damaged forest areas ($Z < -2$) expanded from 1.4% to 10.1% during this period (Fig. 8).

According to the NDVI images (Fig. 8), the damages affected mostly the higher regions of the Bükk Mountains over 400 m above sea level. The most severely damaged area was not in the zone of the highest peaks but in the north-western part of the mountain.

The 16-day standardized NDVI time series from May of 2017 until the end of growing season 2018 showed the abrupt large depression of NDVI after the calamity event (i.e., early May, Fig. 9).

This anomaly was mainly caused by the strong late frost that induced a prompt leaf loss of the trees, especially for beech. The standardized NDVI (Z NDVI) was still below the mean values for the rest of the year, but the negative deviation of Z NDVI remained moderate (< −1). This could be explained by the field observations that revealed that the trees that had lost their leaves formed new shoots later during the spring of 2017. In 2018 only small patches of negative Z NDVI were left, demonstrating that the forests could recover almost everywhere from this event with the new vegetation season, except the heavily damaged areas where sanitary cutting of the forests was conducted.

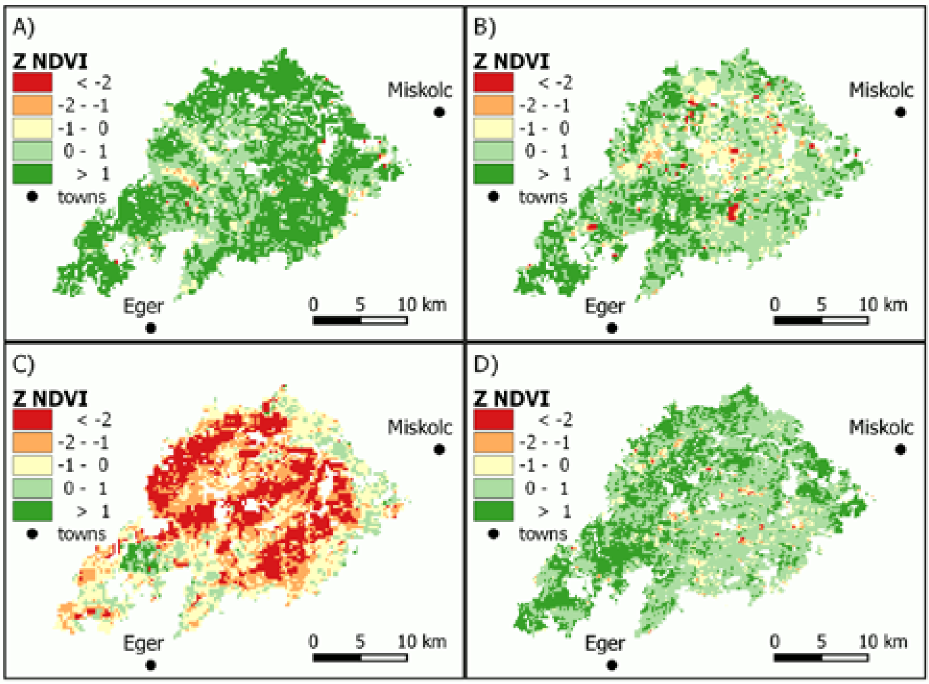

Fig. 8. Forest state of Bükk Mountains based on TEMRE Z NDVI (day/month/year).
A) 18/7/2015. B) 18/7/2016. C) 16/5/2017. D) 19/8/2018.

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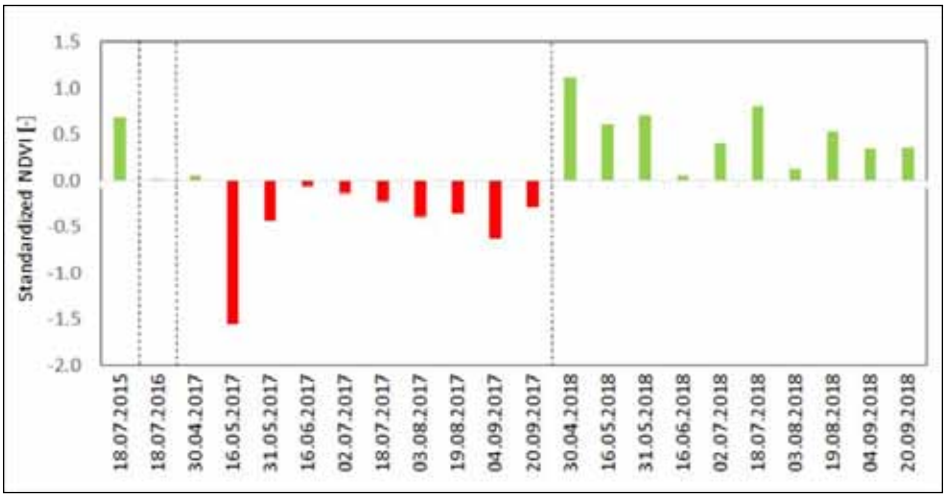

Fig. 9. Time series of standardized NDVI for the Bükk Mountains (2017–2018 and two observation dates for 2015 and 2016 as references).

5. Discussion

5.1. Comparison with regional phenological studies

Regarding the altitudinal gradient of beech forest in Slovakia, Schieber et al. (2013) during the period of 2007 – 2011 discovered that the phenological gradient for spring phenophases ranged from +2.83 to +3.00 days per 100 m and from −1.00 to −1.78 days per 100 m for autumn phenological phases. Positive value means later, negative value earlier onset.

Regarding the altitudinal gradient of phenophases, Bucha & Koreň (2017) confirmed trends similar to ours in a study focused on phenological temporal and spatial changes of beech forest in Slovakia in period 2000 – 2015. In their study, the multiple linear regression analyses revealed altitudinal shift of GSD and DSD onset of 1.6 (−0.6) day per 100 m, whereas latitudinal shifts were 3.7 (0.83) day per 100 km to the North and the longitudinal shifts were approximately 0.24 (−0.23) day per 100 km to the East.

Our results, related to GSD onset in 2018, are consistent with both regional studies in term of +/− trends. However, the estimated altitudinal GSD shift of 0.82 day per 100 m and latitudinal shift 1.05 day per 100 km to the North were moderate in comparison to the above-mentioned studies.

Concerning DSD, the estimated altitudinal shift of −0.79 day per 100 m confirmed the trends from previous studies; however, the longitudinal shift of −1.20 day per 100 km to the East was stronger.

A much broader extent of macro-regional analysis in the direction of latitude revealed that the latitudinal shift −1.17 per day 100 km to the North in study region was completely opposite to the trend observed in Slovakia in 2000 – 2015 period (0.83 day). This could be influenced by selecting just one year (i.e., 2018) or by broader analysed region.

The regression coefficients of the multiple linear regressions between the dependent and independent variables (GSD, DSD vs. altitude, latitude, longitude) are not directly comparable with those of simple linear regressions. In case of regional studies, the results underline the need to further study the complexity of the spatial variability of phenological events in relation to altitude and geographical location.

Phenological modelling in the presented study was based on Fisher & Mustard's (2007) definition of the date of leaf unfolding (leaf fall) as the date on which the sigmoid function reaches its half-maximum value. However, based on the comparison of our findings with those of our previous ones, we modified our approach. We found that NDVI values of beech forest in the period without leaves were different in spring and autumn. Moreover, the NDVI values were slightly lower than the maximum values in the end of summer period. Therefore, we performed the calculation of $m_1 – m_4$ parameters of formula [1] twice, once for deriving the spring phenophase and the second time for deriving the autumn phenophase with v_{min} and v_{amp} parameters different for each phase.

5.2. Tree-rings vs NDVI values

Tree-ring chronologies are not suitable for monitoring of forest growth over large areas due to the time-consuming work of tree-ring preparation (Vicente-Serrano et al. 2016). In contrast, the remotely sensed NDVI indicates the photosynthetic activity of the forest canopy can be used to estimate vegetation productivity (Lopatin et al. 2006). Although the inter-comparison of NDVI, drought indices and ring width index could lead to a better understanding of the response of a forest to recent climatic trends, results of such inter-comparisons still can be found in the literature only rarely (e.g. Camarero et al. 2015).

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In general, the tree-ring width vs NDVI relations of the present study are comparable to those found for conifers in mid-latitudes in the Northern Hemisphere (Lopatin et al. 2006; Bhuyan et al. 2017; Kaufmann et al. 2008). A similar positive relationship between NDVI of June to August and conifer growth was found by Lopatin et al. (2006) and Bunn et al. (2013) for Siberia using NOAA AVHRR PAL and GIMMS NDVI data. Similarly, for North America, studies have reported positive associations between NDVI and conifer ring-widths for Canada (Berner et al. 2013).

A recent study of Bhuyan et al. (2017) used also the 250 m spatial resolution MODIS NDVI for correlating with tree-ring data of forests types in different climate zones of the Northern Hemisphere. They found that the growth of conifers in the temperate climate zone was in tight relationship with the NDVI of summer months with up to 10 cumulating periods. Their analysis was constrained by the fact that no further information about the forest sites (stand and site conditions) was available. In the present study, it was possible to use a pre-filtered database for the analysis despite the fact that it was spatially representative only for a small region.

The autumn and winter weather conditions of the preceding year had almost no effect on the NDVI of the next summer. This can be explained by the low soil water capacity of the selected sites that enhanced the importance of precipitation, as found also by Móricz et al. (2018).

5.3. Field-based forest health assessment vs NDVI values

Vitality loss might happen due to abiotic (snow break, windfall, leaf loss, heat, drought) or biotic causes (pests, pathogens) resulting in physiological deficiencies or leaf loss. If discolorations are detected on larger areas and are sustained over longer time (weeks or rather months), a field survey is essential to verify the satellite indicated issues and further explore the nature of the damage.

The low correlation between the ground-based damage data and the MODIS NDVI in our study may be explained by three major factors. First, the surveyed damaged area, and thus the amount of field data, available for analysis, was very low as there are still large areas with missing data due to inaccessible terrain. Second, the method used for aligning the ground-based field data to the corresponding MODIS pixels could only make use the area of the sub-compartments occupying under each of the MODIS pixels. This method might lead to bias since the shape of the sub-compartments is variable. Quite often, a number of sub-compartments with varying damage severity had to be attached to the same MODIS pixel. For that reason, we included only those MODIS pixels in the analyses whose area was covered by one or two forest sub-compartments. Inevitably, only a small fraction of original data was left for the analysis. Finally, field assessments showed a spatially very heterogenic distribution of forest damages even within the sub-compartments with numerous tree species. This reinforced using the importance of the selected methodology. Although an area-weighted approach could rectify some of the above issues, this would require more detailed input field measurements than what we had access to.

6. Conclusions

By focusing on a macro-region of Pannonian lowland and Western Carpathians, this paper demonstrated that the MODIS-based satellite applications in medium spatial resolution can be successfully used for regional assessment of forest health and phenological phases. Positive associations between annual tree-ring width and summer NDVI was found for conifers at local scale which confirmed the results of previous large-scale analysis.

Further modelling of regional phenology development is needed in order to provide a better explanation of spatial variations of phenological events, especially if the results are to be transferred into species selection practice in forest restoration (after planned logging or disturbances) in relation to forest adaptation to climate change. For a more successful study of forest health, an urgent demand for more detailed field data is obvious.

Acknowledgements

The collaborative research reported by the present study was conducted with the support by the Slovak Research and Development Agency under Grants APVV-15-0413 and APVV-16-0325, by the project ITMS "26220120069 Centre of excellence for decision support making in forest and landscape", funded by the Operational Programme Research and Development financed from the European Regional Development Fund, as well as the EMMRE monitoring program funded by the Hungarian Ministry of Agriculture. The authors thank the NFCSO Forestry Department for giving access to the Hungarian National Forest Damage Registration System data.

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Cent. Eur. For. J. 65 (2019) 218–222 sciendo DOI: 10.2478/forj-2019-0015

CENTRAL EUROPEAN Forestry Journal

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ORIGINAL PAPER

Possibilities of image analysis for quality wood sorting

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Abstract

Wood assessment optimization should be the top priority of the forestry subjects that are fundamentally dependent on the income from its sale. The aim of this paper is to analyse the beech, oak and ash tree logs that were categorized into quality classes according to the size of one of the qualitative characters related to the surface area (false heartwood, rot). The classical methodology used in forestry was compared with the application of ImageJ software. In total, thirty logs were analysed. The characters of false heartwood and rot were chosen and evaluated according to their size on the log end. There were no other characters that obstructed the categorization into quality classes. The ImageJ software application led to improved assessment (transfer to a higher quality class) in 56% of the logs. The volume of the evaluated assortments was 18.43 m^3. The total difference in the value of the assortments with the ImageJ software application reached + €70.44 (+ 4.7%). The analysis therefore confirmed that in case of a considerable irregularity in a qualitative character (when the surface area of the character significantly differs from the circumscribed circular surface), the standard STN EN 1309–3 methodology systematically overvalues the surface area of this character. That affects the assessment potential of the specific log.

Key words: log quality; wood sorting; image analysis; wood proporties

Editor: Miloš Pánek

1. Introduction

Evaluation of the produced wood consists of assessing the size of its qualitative characters and technical conditions that define the allowed or unallowed size of these characters. Since the qualitative wood evaluation according to its positive qualitative characters is not yet possible, it is evaluated only according to the occurrence and size of the negative qualitative characters (wood defects). This evaluation method develops a quality framework that constitutes the basis for the seller-buyer relationship. The seller and the buyer can stipulate specific conditions as well as price levels depending on the basic quality sorting defined by the technical conditions (Hein et al. 2007; Gejdoš & Danihelová 2015). For the optimization of the produced wood evaluation it is necessary to know the qualitative characters of the wood and their measurement and assessment methods. In the European trade area they are defined primarily in the standards STN EN 844–8 "*Round and sawn timber. Terminology. Part 8: Terms relating to features of round timber"* and STN EN 1309–3 "*Round and sawn timber. Methods of measurements. Part 3: Features and biological degradations"*. In the forestry practice, the qualitative characters are assessed and measured either manually (by visual evaluation), or electronically (mainly through scanners). The electronic evaluations and measurements require the investment in devices as well as construction works that are not profitable in forestry. Usually they are bought only by timber processors with a high concentration of wood stock inventories where the application of electronic devices increases the economic profit (Gergeľ et al. 2019). There is a relatively wide range of software tools that offer a simplified analysis of qualitative characters. Most of them are paid applications. However, there are also free software tools that can evaluate the surface area of certain qualitative characters from high-quality photographs (Gejdoš et al. 2014). The irregular shape of the qualitative characters evaluated according to their surface area (like rot, discolouration, false heartwood, spalting, reaction wood) can cause significant measurement deviations, since according to the STN EN 1309–3 the diameter of the circle circumscribing such a character has to be measured. This method significantly overvalues the surface area of the character. Software tools use photographing analysis that enables considerably more

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accurate evaluation of qualitative characters, as they can determine the exact value of such a character on the surface of the log. The aim of this paper is to verify whether the application of the ImageJ software tool for the qualitative analysis of the selected broad-leaved trees logs is a suitable alternative for qualitative assessment of wood. The classical approach used in forestry was compared to the application of ImageJ software. The software tool should enable economically more effective assessment of raw wood assortments, where the size of qualitative characters determines the categorization into quality class.

Presence of false heartwood and its percentage has a significant impact on the possibilities of its assessment and on the purpose of its use. Many authors described the efficiency of the logs with false heartwood in its processing from the sawing process to the end product: Petráš (2015) created the models for assessing the growth and production of the forest covers. Račko & Čunderlík (2006) proved that false heartwood occurs in 1/3 of the beech logs, mainly in older trees. It is caused by many factors, their influence was analysed in the papers of (Račko & Čunderlík 2010). The authors compared age of the trees, dimension of the trees, representation of tree species in the forest cover as well as size of the tree crowns. It was concluded that the most significant factor affecting the presence and creation of the false heartwood is the age of the trees. Crown size and representation of tree species in the forest cover do not have a major influence on the false heartwood presence. A high share of the round timber with false heartwood in beech trees affects its processing into sawn timber. Popadić et al. (2014) studied the influence of the round timber sawing method with false heartwood in beech trees on its assessment. Results suggest that the largest yield was achieved when using round sawing and cant sawing. (Barański et al. 2017) and (Shahverdi et al. 2013) proved that the presence of false heartwood in the beech sawn timber greatly affects the drying process and the final quality of the sawn timber. If the beech wood is used for veneer production, the presence, percentage and shape of the false heartwood also must be taken into consideration. It is necessary to determine the optimum thickness of the beech round timber for veneer production. Bluskova et al. (2008) discovered that the most suitable round timber for veneer production is 400 mm thick.

This overview proves that the share of false heartwood in the beech round timber greatly affects its assessment and this character has to be taken into consideration in every stage of technological process.

2. Material and methods

Thirty logs in total were analysed: European beech (*Fagus sylvatica*) – 26 logs, sessile oak (*Quercus petraea*) – 3 logs, and European ash (*Fraxinus excelsior*) – 1 log. The amount of samples was limited to the availability of tree species in the storehouse in winter as well as to the qualitative characters crucial for their categorization. Only those logs were analysed where the qualitative categorization depended solely on one qualitative character assessed according to its size on the surface area of the log. The qualitative character in beech and ash trees was false heartwood (heartwood by ash). In oak trees it was heartwood rot.

The qualitative characters were at first measured manually according to the standard STN EN 1309–3 (Fig. 1).

Fig. 1. Evaluation of false heartwood on beech according to STN EN 1309–3.

As an alternative for optimization of qualitative evaluation of these assortments the ImageJ software was selected. Its use and methodology of surface area assessment for the beech trees with false heartwood or other characters is described in the papers of (Gurau et al. 2013; Gejdoš et al. 2014; Phonetip et al. 2017; Potkány et al. 2018). Assessment methodology of the characters in this software was adopted from the paper by (Gejdoš et al. 2014). The assessment of the qualitative characters in the software consists of the following steps:

- Production and processing of a digital image perpendicularly to the log axis that has a qualitative character. Manual measurement of the log end diameter according to standard dendrometric rules.
- Digital image processing in the software and determination of the reference dimension (reference dimension is the diameter of the log end in centimetres) – Fig. 2a.
- Highlighting the area of the end log in software – Fig. 2b.
- Highlighting the area of the qualitative character in software – Fig. 2c.
- Calculation of the log end area and the qualitative character area according to the reference dimension. The percentage of the surface area of the selected

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qualitative character on the log end is easily expressed by this simple process. It calculates the exact surface area of the qualitative character without overvaluation. The overvaluation caused by using the standard method is obvious also in the Fig. 1 (the "healthy" wood areas are included in the surface area of the qualitative character). Figure 2 shows the processing procedure in the ImageJ software. This procedure was used on all the analysed logs.

For simple calculations and graphical evaluation, MS Excel 2013 was used. To measure the size of false heartwood steel meter (band) was used, and to measure assortments thickness standardized calliper was used. Photographic documentation was done with digital camera NIKON D5200 with an effective megapixel count 24.1 and lens with a focal length f = 18.0 mm. Printed graphics and other evaluations were performed by the software product ImageJ 1.52a.

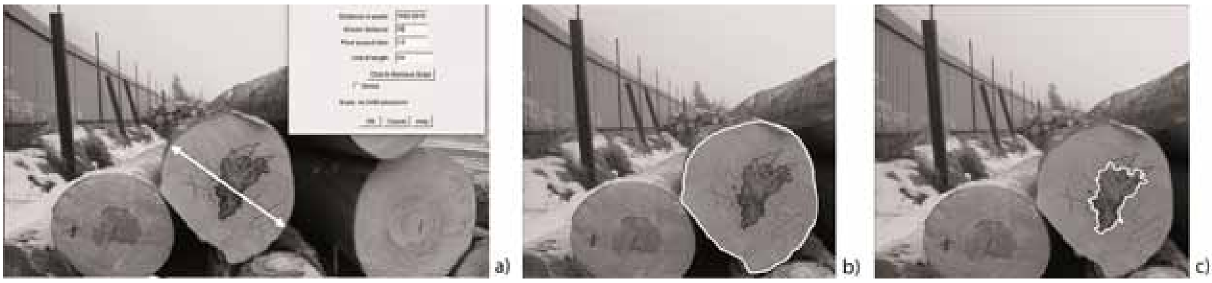

Fig. 2. Evaluation of compression wood in spruce with the ImageJ software: (a) scale determination in cm; (b) log-end area determination; (c) area of false heartwood determination.

The logs were categorized into quality classes according to the 2007 standard STN 48 0056. This standard classifies broad-leaved raw wood assortments. The determinative characters assessed according to the surface area in these quality classes are false heartwood and rot. The allowed area of these qualitative characters in round timber quality classes II. and III. is stated in Table 1. Quality class II. includes logs for peeled veneer production, logs for match production, sports equipment, technical equipment and cask production. The quality class III. wood is used mainly for sawmill processing. In higher quality classes the occurrence of these characters is not allowed. In lower quality classes it is allowed without restrictions.

For assessing the economic efficiency of the ImageJ software, the average Slovak prices from the price list of the Forest Market Information System for the fourth quarter of 2018 were used. The prices in Slovakia are stated in € m^{-3} excluding VAT at CIF level.

Volume of assortments was determined individually by the Smalian formula [1]:

$$v = \frac{\pi}{4} \cdot \frac{d_0^2 + d_n^2}{2} \cdot L \qquad [1]$$

Where:
v – log volume in m^3
d_0 – log thickness (thicker end) in m
d_n – end diameter thickness (thinner end) in m
L – length of log in m.

3. Results and discussion

From the chosen two qualitative characters that were assessed according to the surface area and that were the only restricting characters for qualitative classification, the character false heartwood was identified in 26 beech logs and 1 ash log. The character rot was identified in 3 oak logs. The classification into corresponding quality classes in view of the qualitative characters according to the standard STN EN 1309–3 and technical conditions STN 48 0056 can be seen in Table 1. The assortments were assessed with the ImageJ software and in accordance with the standards. The application of the ImageJ software led to better assessment (transfer to a higher quality class) in 56% of logs. Paradoxically, the price for the quality class I. beech wood in the price list was 116.72 € m^{-3} without VAT and for the quality class II. beech wood 119.28 € m^{-3} without VAT. Therefore, in two cases the transfer to a higher quality class paradoxically had a negative economic impact. However, such situations occur only rarely on the market. This fact is also negatively affected by the long-term situation on the market with valuable logs and beech sawmill round timber. The processors show only little interest in these kinds of assortment. Subsequently, such paradoxes reflect in price lists and implementation of the commercial policy. Table 2 shows the amount of logs classified into the corresponding quality classes according to the standard STN 48 0056 (2007). The qualitative characters of the logs

Table 1. Allowed surface area of false heartwood in beech/ash and rot in oak for the quality classes II. and III. according to the standard STN 48 0056 (2007).

Quality character	II.	III.A	III.B	III.C
False heartwood (beech, ash)	Up to 1/3 area of the end diameter	Up to 1/3 area of the end diameter	Up to 1/2 area of the end diameter	Allowed without restrictions (flame up to 1/2 area)
Rot (oak)	Not allowed	Not allowed	Not allowed	Up to 1/3 area of the end diameter

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were assessed according to the standard STN EN 1309–3 and the ImageJ software algorithm.

Table 2. Division of beech, oak and ash round timber logs into quality classes according to the standard STN 48 0056 (2007) using two evaluation methods.

Quality class / No. of Logs	I.	II.	III.A	III.B	III.C	V.
STN EN 1309–3 Classification	0	6	0	10	9	5
ImageJ Classification	2	3	8	10	2	5

According to the ImageJ software, the average surface area of false heartwood and rot on all log ends comprised 15.35% of the whole surface of the log end.

Table 3 shows the economic evaluation of both methods of qualitative classification of spruce logs. The volume of the evaluated assortments was 18.43 m^3. The total difference in the value of the assortments with the application of the ImageJ software reached + €70.44 (+ 4.7%). A change in the evaluation methodology of qualitative characters assessed according to their size can lead to a more precise evaluation of the produced raw wood assortments despite the aforementioned market paradoxes with the beech round timber.

The analysis therefore confirmed that in case of a considerable irregularity in a qualitative character (when the surface area of the character significantly differs from the circumscribed circular surface), the methodology stated in the standard STN EN 1309–3 systematically overvalues the surface area of this character. That affects the assessment potential of the specific log. In case of oak sawmill round timber the decisive character that significantly restricted qualitative classification was rot. Here the use of new methodology did not lead to qualitative shift of produced assortments. The same applied to ash logs. There was not a sufficient amount of oak and ash tree logs that could definitely prove the positive influence of the new methodology on their assessment. Since beech is the most common tree in Slovak forests where false heartwood occurs quite often, application of this evaluation method on yearly production volume of the beech assortments could lead to significant improvement in their economic assessment.

In the study of Potkány et al. (2018) this evaluation method also led to better assessment of the raw wood assortments produced from spruce sawmill round timber. The qualitative characters of reaction wood, rot and wood discolouration on sawmill round timber were assessed. One hundred logs in total were analysed. Overall, the economic assessment of the wood improved by €426.68.

In the study of Gejdoš et al. (2014) the ImageJ software analysed 63 logs with false heartwood. Such evaluation method also led to better assessment of the wood assortments, in comparison with the classical evaluation according to the standards, by €399.54. However, this study also included logs that were categorized into quality classes not only according to the size of the qualitative characters related to the surface area. The assessed logs came mostly from tending felling. Our study analysed only the logs that were categorized into quality classes solely according to the size of the qualitative characters related to the surface area and the assessed logs came mostly from principal felling.

All studies therefore confirm that if the size of the qualitative characters related to the surface area was analysed more precisely, the qualitative classification would be more accurate and the overall assessment of the assortments would be higher. In Slovakia, the sales of the sold wood comprise almost 90% of the forestry incomes. Therefore, seeking ways to optimize the assessment of raw wood assortments should be the top priority of forestry practice and research.

4. Conclusion

The disadvantage of using the ImageJ software is that for the time being it is not a part of standard legislation for assessing the qualitative characters of the logs. Another disadvantage is that it is not quite possible to unify the methods of taking and evaluating photographs in the working practice (different parameters of cameras, camera angles, lighting conditions, etc.). However, it is a simple tool that could be used even in difficult conditions of forestry practice. For these purposes, there are already some similar tools used in the forms of various mobile applications or software solutions for mobile devices. In forestry, using the CT scanners and tomographs for size detection of qualitative characters is not profitable for operational and economic reasons. Incorrect qualitative assessment often leads to wrongful categorization of logs into lower quality classes and to decreased potential for higher-quality processing (Hajdúchová et al. 2016). The software possibilities are being dynamically developed

Table 3. Economic assessment of the analysed beech, oak and ash round timber logs using two evaluation methods.

Quality class/No. of Logs	Price in € m^{-3}			Volume of Logs according to STN EN 1309–3 [m^3]	Total Price in € m^{-3}* According to STN EN 1309–3	Volume of Logs according to ImageJ [m^3]	Total Price in € m^{-3}* according to ImageJ
	beech	oak	ash				
I.	116.72	480.16	—	0	0	3.11	363
II.	119.28	309.99	200.04	5.18	617.87	1.6	190.85
III.A	76.93	214.1	120.71	0	0	4.76	366.18
III.B	60.02	164.5	90.74	5.62	377.02	5.99	399.22
III.C	54.49	76.16	58	5.9	348.36	1.24	94.44
V.	44.79	41.96	43.64	1.73	77.22	1.73	77.22
Total	—	—	—	18.43	1420.47	18.43	1490.91

* Prices according to Forest market information system.

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also in forestry. Together with the potential for greater application increase the demands on knowledge and experience of the management and people assessing the logs. It is therefore important to be willing to implement innovations, to test them and to subsequently use them in forestry practice. At the same time it is necessary to adjust the corresponding standards, technical conditions and legislation in such a way that it will be possible to optimize the qualitative potential of raw wood assortments. However, the processors will most probably not be willing to change anything in this area because it could have a negative impact on their economic balance. Nevertheless, the results of this study show that the innovative way of assessing the qualitative characters can lead to a more accurate evaluation of qualitative characters and therefore to the optimization of raw wood assortments evaluation.

Acknowledgements

This work is part of the VEGA Nr. 1/0031/18 project Optimization of technological and work processes and risk assessment in the production of forest biomass for energy purposes, MPRVSR item 08V0301 – Research and development to promote forestry competitiveness (SLOV – LES) and OPVaI International Teaming Research Centers.

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Cent. Eur. For. J. 65 (2019) 223–232 sciendo DOI: 10.2478/forj-2019-0016

CENTRAL EUROPEAN Forestry Journal

ORIGINAL PAPER

http://www.nlcsk.sk/fj/

Marketing support of decision-making at the forest enterprise: A case study on roundwood assortments portfolio

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Abstract

This paper focuses on the marketing support of decision-making at the forest enterprise on the example of forestry products, concretely, of roundwood assortments on the chosen state forest enterprise in the Slovak Republic. The most used marketing decision-making models as SWOT, BCG, and GE matrices with support of ABC analysis were used for chosen research purpose. Additionally, these models were compared to confirm their reliability and expressing power for marketing management of forest enterprise. The conclusions confirm that the use of these models build a strong framework for the decision-making support of forest enterprise management. The outcomes of models contribute to each other and they do not contradict. However, it is necessary to have a strong base of forestry practice knowledge due to the correct interpretation of these models. In contrast to other industrial companies, forest sector is a very specific regarding the long rotation and payback period. The main pillar of the product portfolio and forest enterprise either are assortments of the III. qualitative class and broadleaf pulpwood with the 86% share on total revenues. Concerning the prevalence of threats and company strengths, it is necessary to choose diversification management approach for the product portfolio.

Key words: decision-making; marketing; models; forest enterprise; strategic management

Editor: Miloš Pánek

1. Introduction

Trade with roundwood is the most important source of income for preserving the functions of forests and maintenance of the employment in the forestry sector. More than 80% of the revenues of forest enterprises are provided by the sale of roundwood in the Slovak Republic (Ministry of Agriculture and Rural Development of the Slovak Republic 2018). Besides of the forest sector, wood is the main raw material also for the wood-processing industry therethrough the employment, revenues and profits are provided also in this area of the Slovak economy as well (Kaputa et al. 2016; Parobek et al. 2014; Paluš et al. 2015, 2018). In generally, global but also regional demand on wood consumption for the power, construction, and furniture industry will furthest raise (FAO 2018; Jochem et al. 2016; Herrera 2018). According the FAO (2018), the main factors affecting long-term global demand for wood products include: i) increase of the world's population, ii) continued economic growth, iii) the rapid growth of developing economies, iv) the environmental policies and regulations inducing decline in harvesting from natural forests and the emergence of planted forests as the major source of wood supply and v) the energy policies with the emphasis on the use of forest biomass.

Therefore, from these objective results it comes out a great opportunity to realize marketing approaches just in the area of selling wood (Elyakime & Cabanettes 2009; Lovrić et al. 2018; Rönnqvist et al. 2018), and non-wood forest products on the market (Ludvig et al. 2016; Šišák et al. 2016; Huber et al. 2017; Neis et al. 2019) and to evaluate and market the extra benefits of forests also known as non-productive functions of forests (Sarvašová et al. 2014; Sarvašová & Dobšinská 2016). However, the use of marketing management in forestry is of less interest of research agenda, what also results from the low level of publicized scientific works with the application of marketing principles in this sector (Ok 2005; Greppel et al. 2009). Additionally, the range of marketing in the forest management is low. In other words, it has been not enough space dedicated to it (Brodrechtova 2008).

The forest enterprises stay as a producer of roundwood at the end of the chain of derived demand on wood (Cooper 1990; Chirinko & Mallick 2011; Knauf 2015). The fast-varying conditions on the markets with the

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consumer goods affect indirectly the forest enterprise by change of their customers' wants and needs. This situation requires strategic oriented marketing (Hansen & Juslin 2011). The forest enterprise could on one side rapid and flexible react on the market variations, on the other side, use the opportunities on the rising markets (Owari et al. 2006; Kim et al. 2018).

The application of decision-making models in marketing management of forest enterprises is very rare despite of their high expressing power for management process and especially the possibility to assess the product or customers' portfolio (Halaj et al. 2018). They are used more in other sectors of national economy, e.g. food industry (Seggie 2007; Torquati 2018) or to evaluate the investment funds or financial statement on the capital markets (Haltofová & Štěpánková 2014; Chen et al. 2015).

This case study was carried out on the selected state forest enterprise in the Slovak Republic. It applied methods of decision-making models on product portfolio of broadleaf and coniferous roundwood assortments.

The aim of the paper was to point out of the significant marketing role in the forest enterprise management, to stress the use of decision-making models on the specific example of forestry products and to compare selected models according the chosen indicators.

2. Material and methods

The selected state forest enterprise operates on the forest area of 52 094 ha, with the forest cover 40.5%, and the share of coniferous with 29% and broadleaf forest 71%. The annual amount of harvested roundwood is in the range of 185 000 – 200 000 m^3 with the average annual revenues in amount of 8.3 million € (2017). The necessary secondary data were taken from the report of the company management, concretely from the profit and loss statement. For the research purpose, the data about revenues for individual broadleaf and coniferous roundwood assortments were analysed for the period of 2016 – 2017. There had to be also primary data needed for one of the decision-making models (GE matrix) in form of subjective opinions of experts.

This paper was focused on the use of marketing decision-making models for the evaluation of the product portfolio by reason of the management of forests production function. Therefore, the portfolio analysis of the roundwood assortments was carried out by the SWOT analysis – the SWOT, Opportunity and Threat matrices (Samejima et al. 2006; Kajanus et al. 2012; Kotler & Keller 2015), BCG Growth-Share matrix (Meffert et al. 2014; Kotler & Keller 2015), the Mckinsey GE matrix (Baran 2007; Baum 2012) and ABC analysis also called the curve of the turnover concentration (Jacobs et al. 2010; Wild 2017) in the selected forest enterprise. These models were chosen by reason of their generality and the highest rate of utilization in managerial practice.

2.1. SWOT analysis

The SWOT analysis as a decision-making model was chosen for the evaluation of the strengths and weaknesses of the given product portfolio and also for the opportunities and threats on the market with the roundwood assortments. The SWOT, opportunity and threat matrices are as a results of the evaluation process. At the same time, the matrices offer the proposal of the marketing strategy for the product portfolio or present the marketing decision-making support.

The SWOT indicators were identified by forest enterprise management. They were subsequently assessed in two way methodological approaches.

First, the company management evaluated the indicators regarding their strengths or weaknesses by Likert scale from the strongest (2) to the weakest (−2). Afterwards, the seriousness was bind to each indicator in the scale from the low (1) to the highest (3). The indicator could reach by multiplying of both values the maximum positive value of 6 (means strength or opportunity) or the maximum negative value −6 (weakness or threat). The evaluations of all four company managers were averaged and so the two values (difference between strengths and weaknesses and opportunities and threats) giving the point coordinates (axis x and y) were obtained (Fig. 1). The searched point could lie in one of the four quadrants where each of them presents concrete marketing strategy proposal.

Second, the strengths and weaknesses were also evaluated by Likert scale from the strongest (5) to the weakest (1) and to them pertaining seriousness from the low (1) to the highest (3). The final pair of values for each indicator defines coordinates of points in related SWOT matrix (Fig. 2). By opportunity and threat matrix (Fig. 3 – 4), the probability of occurrence and success (axis x) were assessed by Likert scale within the threats from the biggest risk (1) to lower risk (2) and within the opportunities from average success (3) to biggest chance (5). The seriousness of indicators was divided into seriousness of risks and chances at the same scale from 1 to 3. The coordinates of points in the opportunity and threat matrices were calculated at the same manner as in the SWOT matrix.

2.2. BCG matrix

The design of the BCG matrix is based on the two parameters, namely the relative share of SBUs (Strategic Business units) on the total revenues and the rate of the revenues growth, or growth index. The relative share on the total revenues is described by following formula:

$$Relative\ share_n = \frac{Revenues\ SBU_n}{Total\ revenues}\ x\ 100 \qquad [1]$$

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where

relative share$_n$ is the share of n-product on the total revenues [%],

revenues SBU$_n$ are revenues of n-product (SBU$_n$) in the current period,

total revenues are revenues of all products (SBU) in the current period.

The growth index of the revenues (i_n) is the ratio indicator measured by relation of the n-product (SBU_n) revenues in the current year to revenues in the previous one:

$$i_n = \frac{Revenues\ SBU_{n\ current\ year}}{Revenues\ SBU_{n\ previous\ year}} \qquad [2]$$

The relative share of revenues introduces the horizontal axis (x) in the BCG matrix. The median value of the achieved shares of SBUs in total revenues signifies a limit between high and low relative shares. The vertical axis (y) represents the growth index of revenues, where value 1 is considered as the limit between high and low growth index. Based on the limit values of the relative revenues share and revenues growth index, the BCG matrix is divided into four quadrants: cash cows, dogs, question marks and stars. In general, all SBUs situated in the quadrants cash cows and stars achieve positive cash flow and they are perspective for the enterprise. On the other hand, the SBUs placed in the quadrants question marks and dogs require significant investment and may reach low profits or even losses (Evans & Berman 1990).

2.3. GE matrix

The GE matrix is one of the decision-making models which balances some limitations of the BCG matrix for more investigated factors in two main dimensions (Baran 2007; Baum 2012): competitive position (axis x) and market attractiveness (axis y) of the selected products, or services (SBU). In this case, the competitive position covered following nine factors: i) relative market share, ii) distribution channels, iii) product quality, iv) product trademark and image, v) costs, vi) relative profit, vii) production effectiveness, viii) product promotion and ix) innovation abilities. The market attractiveness consisted from these specific nine factors: i) market capacity, ii) rate of market growth, iii) competition, iv) state regulations, v) market profit, vi) technological development, vii) barriers to entry and exit, viii) capital intensity and ix) seasonality. All evaluated factors were adopted from Blažková (2007) and considered by selected experts from the forestry sector.

The methodology for setting up of the GE matrix consisted of (Horáková 2003; Blažková 2007):

a) the identification of factors for individual dimensions (axis x, y),
b) defining the selected factors,
c) ranking the wages of each factor by selected six experts in the given field. The individual wages were afterwards averaged by weighted arithmetical average,
   – the wages presented the significance of individual factors which sum equals one (1)
   – factor importance – the current state of each factor or the dependency level on given category of selected factor was rated by enterprise management, the ratings were in range of 1 to 5 (1 – unattractive, 5 – very attractive).
   – final value of the factor – multiplying the wages with the ratings presented the final value for each factor.
d) finding the values of both dimensions (axis x, y) – presented the sum of the total values of factors by individual product types – roundwood assortments,
e) placing the (SBU) units into the portfolio matrix by bubble diagram in Excel,
f) displaying the range of the circles (bubbles) which were equivalent to the markets size of individual products (SBU) and
g) proposing the marketing strategy for each product (SBU) in the portfolio matrix.

The interpretation of the GE matrix by Blažková (2007) was used to examine the product portfolio. Following zonation into the nine fields or three zones was applied:

1. Top left – strategic profitable position of a products or services (SBU) in which the enterprise should invest and support their growth. It presents the strong advantages for the company. Sometimes it is called as a “green zone”.
2. Diagonal – middle advantage strategic position of products or services (SBU). It is necessary to consider into which field to invest. This area of matrix is also termed as the “yellow zone”.
3. Right down – unattractive position of the SBU. The enterprise must decide how it evaluates the individual fields of business or it rejects them. This zone is also called the “red zone”.

Splitting the GE matrix into the equal nine fields required to fractionate both axis (x, y) into the three identical parts according to theoretical framework (Baran 2007). The range of each axis was given by the evaluation scale of identified factors from 1 – unattractive to 5 – very attractive. Therefore, the final range of each field in the matrix had the value of 1.33.

2.4. ABC analysis

Also known as the analysis of the turnover structure shows the share of individual products, services or customers on the total turnover in terms of revenues. The results of the analysis provide the information about the turnover concentration and remind on the very strong dependence on several products, services or customers.

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The revenues of the individual products or services were counted by following formula:

$$R_i = D_i \times P_i \quad [3]$$

where
R_i – total revenues of the i-product,
D_i – deliveries of the i-product and
P_i – price of the i-product.

Total revenues were calculated as:

$$R = \sum_{i=1}^{k} R_i \quad [4]$$

where
R means the total revenues from all products,
k is the number of produced products and
R_i are the revenues of the i-product.

Within the ABC analysis, the individual roundwood assortments were categorized into the three groups according to their relative share on total revenues (Šulek 2004; Greppel et al. 2009):

– A group: roundwood assortments of the III. qualitative class (saw logs)
– B group: pulpwood and other industrial wood assortments of the V. qualitative class
– C group: assortments of the I., II. qualitative class (veneer, plywood) and fire-wood

In this case, the relative number of individual products (axis x) came out from the total number of roundwood assortments (5). Therefore, the A and B group had at one fifth (20%) products and C group at three fifths (60%).

3. Results

The management of forest enterprise identified by SWOT analysis the strengths, weaknesses, opportunities and threats of the roundwood assortments portfolio as follows (Table 1).

The prevailing strengths over the weaknesses (axis x = 22) and threats over the opportunities (axis y = −13) are the findings of the evaluation of individual indicators (Fig. 1). The diversification strategy is the recommendation for the given type of the product portfolio in the certain market place.

The reference of the proposed strategy is to decrease the impact of prevailing external threats on the selected product portfolio. Therefore, it is necessary to e.g.: i) substitute the indigenous species by species with skills to master current changing climate regarding the locality conditions, ii) adapt the silvicultural and exploitation processes to changing climate conditions, iii) adjust the share of own harvesting and transport facilities for necessity of prompt reaction on processing wood of gale-disaster areas, iv) optimize the portfolio of roundwood purchasers regarding the contracts length, price of roundwood assortments, product structure, etc.

The marketing strategy proposal is very narrow linked to the results of the SWOT, Threat and Opportunity matrices (Fig. 2 – 4). Figure 2 shows, that most of the indicators are the strengths with the high seriousness what is the baseline for achieving the company's profit or maintenance the market position. Therefore, the recommendation is to focus on these indicators (see Table 1) and to keep their position with the correct managerial approaches.

Coming from the comparison of the threat and opportunity matrices (Fig. 3 – 4), the prevalence of threats is evident. Therefore, suggested marketing strategy is to diversify the product portfolio. However, the best part of threats are indicators with less seriousness. Even thought, the probability of their occurrence needs to be spotted. In the present time, the indicator of invasive tree species (5) was considered as the less significant and the most substantial was the threat by bark-beetle (7) for chosen forest enterprise.

The BCG matrix at the company level reflects the situation on the domestic market with the roundwood assortments in the given period (2016 – 2017). It shows the balance rate of products in the company portfolio as well as its marketing strategy. The main pillar of the investigated product portfolio are coniferous and broadleaf assortments of III. qualitative class and broadleaf pulpwood (positions of cash cows and stars in the Fig. 5).

Table 1. SWOT indicators of the product portfolio.

Strengths	Weaknesses
1. quality of roundwood processing	6. lower price of roundwood assortments comparing with the neighbouring countries
2. amount of roundwood assortments	7. price competition among the roundwood assortments within the product portfolio
3. roundwood availability	8. degree of processed roundwood into the assortments (question of added value)
4. guarantee of roundwood suppliers	
5. market share of roundwood assortments	
Opportunities	**Threats**
1. subventions for forest machinery revitalisation	5. invasive tree species
2. increasing demand on wood as a building and interior material	6. political influence 7. bark-beetle
3. bioeconomy (green energy)	8. gradation of wild animals
4. pricing regulations of forest ecosystem services	9. climate change
	10. endangered tree species (spruce, fir, beech, oak, hornbeam)
	11. increasing area of protected areas
	12. strategy of the environmental policy of the Slovak Republic till 2030
	13. adverse development of the wood-processing and furniture industry

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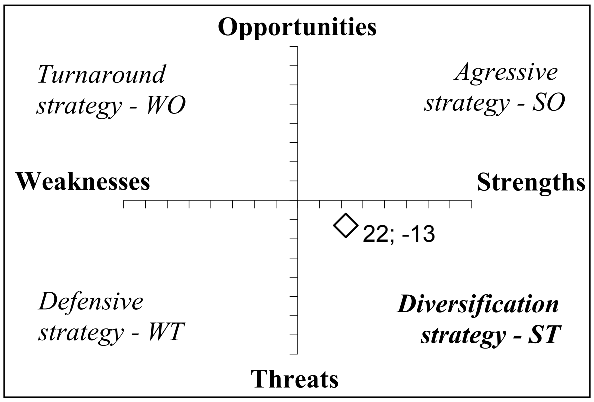

Fig. 1. Proposal of the marketing strategy.

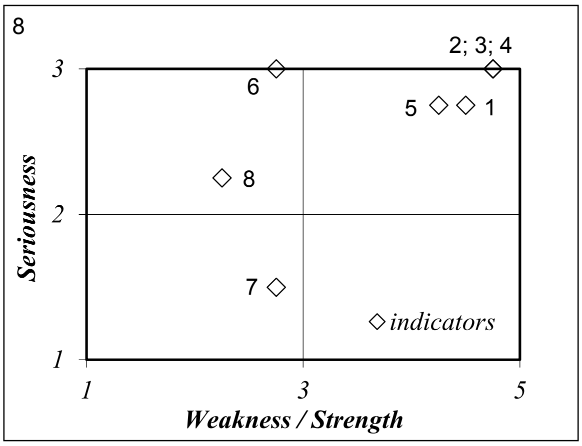

Fig. 2. SWOT matrix.

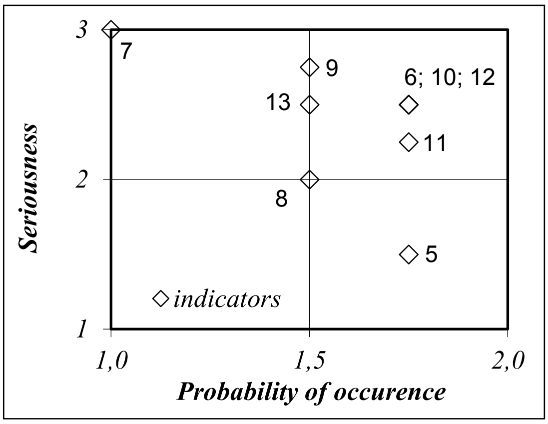

Fig. 3. Threat matrix.

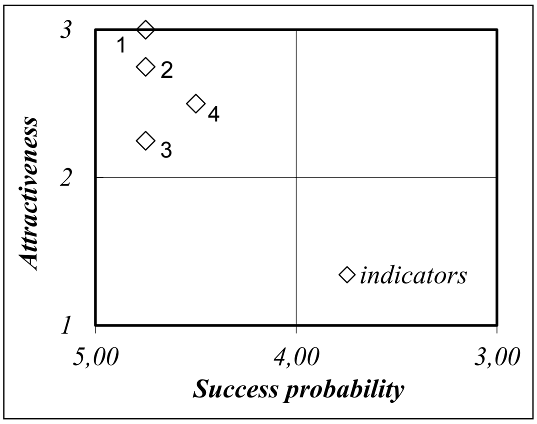

Fig. 4. Opportunity matrix.

These SBUs present 86% of total revenues coming from the sale of roundwood. This state confirms the prevalent demand on roundwood for production of sawn timber and pulp and paper on domestic market. From the pure economic viewpoint, other products (roundwood assortments positioned in the field of question marks and dogs) are unattractive SBUs according to their total amount and relative share on revenues, and growth index (assortments of I. II. qualitative class and fire-wood). Despite of the position of coniferous pulpwood in the matrix (dogs), it is traded together with the broadleaf pulpwood resulting from the business contracts with the dominant purchaser on the market. Therefore, it cannot be considered as unattractive.

In generally, seeing the particularity of roundwood assortments production in the forest sector, it is impossible that some of these products will be rejected from the portfolio or they would be not produced. Thus, the unattractive assortments used to be a part of the aggregated wood assortments, what is the case of I. II. qualitative class as a part of the III. class and pulpwood as part of the fire-wood by heat production. Additionally, assortments of the I. II. class like resonance wood, wood with specific structure etc. are usually traded by auction sale.

The results evaluation of the product portfolio by GE matrix (Fig. 6) shows similar findings in comparison with BCG matrix. The assortments of the III. qualitative class have the highest rate of the competitive position and market attractiveness where broadleaves reach a bit higher market share with 2.79% as the coniferous with 2.01%. They are situated in so called "green zone", the coniferous partly also in diagonal of the portfolio. However, these present the highest amount of revenues in the product portfolio. The broadleaf (with the market share of 1.71%) and coniferous (1.44% of market share) pulpwood is placed in so called "yellow zone", in the diagonal of the product portfolio. So, they are a little bit less attractive but still the most important for pulp and paper industry. The last portfolio products as assortments of fire-wood and I. II. qualitative class are in the "red zone" of the matrix. The biggest market share has the coniferous fire-wood with 2.48%. The market share presents the product share from the company portfolio on the market capacity which is the sum of all realized revenues by state and non-state forest enterprises. However, the results and recommendation lead to same findings as by the BCG matrix. Despite of their position in the red zone, it is impossible not to produce them.

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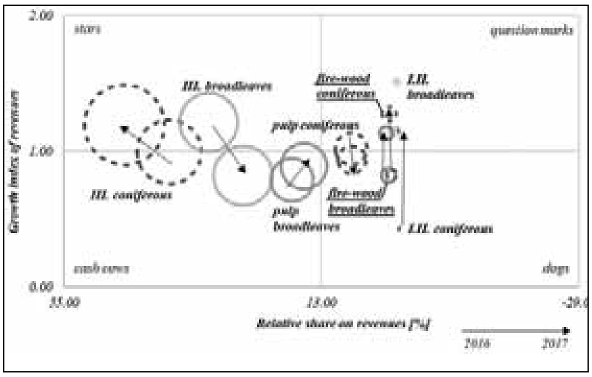

Fig. 5. BCG matrix of the roundwood assortments portfolio in the period 2016 – 2017.

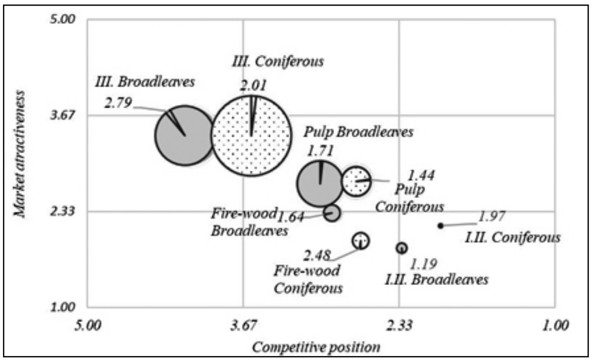

Fig. 6. GE matrix of the roundwood assortments portfolio in 2017.

The results of the ABC analysis (Fig. 7) point out that forest enterprise should pay the greatest attention to the A group of wood assortments (III. qualitative class of saw logs). This group reaches the highest amount of turnover by number of 20% products by both wood species (81.40%; 57.99%) in investigated year 2017.

This score confirms the Pareto rule especially by coniferous roundwood portfolio. Another 20% of products (B group) present the share of 14.71% by coniferous and 35.66% by broadleaf pulpwood. The C group despite of 60% product count reaches the rate only between 4 – 6% share by coniferous and broadleaf wood assortments.

It results from the used decision-making models that chosen forest enterprise should furthest focus on the production and sale of roundwood assortments within the III. qualitative class and pulpwood. It will be depending on several factors, for instance: i) the growing stock of individual assortments in the forest stand, ii) share of demanding wood species as e.g. spruce, beech, oak in the given qualitative classes, iii) economic and technical availability of roundwood assortments in the forest stand, iv) derived demand from wood-processing, paper and pulp, and furniture industry on roundwood assortments and v) cost and price range of roundwood assortments, etc.

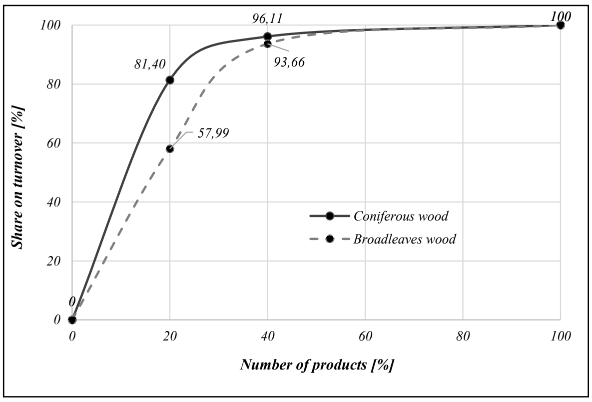

Fig. 7. ABC analysis (the curve of turnover concentration) of the roundwood assortments, 2017.

Following the application of the decision-making models in practice, their advantages and disadvantages were evaluated and compared with the viewpoint of the forest enterprise (see Table 2). Within the outcomes from individual decision-making models, it can be stated that they represent a compact view about the product portfolio in the selected forest enterprise. They are a remarkable tool for decision-making of the forest enterprise management.

However, they require to know the production process and character of products. It helps to increase the quality of the results interpretation which can be otherwise very misleading. Each model brings its viewpoint or certain added value into the managing process. At the same time, models dispose with the similar information, which means that their results should not be contradict but complement.

Table 2. Comparison of the selected marketing decision-making models.

Decision-making model	The viewpoint of the technical use		The viewpoint of the forest enterprise
	Advantages	Disadvantages	
SWOT analysis	consideration of key company priorities; enables organization to set achievable goals, objectives, or strategy	snapshot of the company at a particular moment in time; easy to mislead by identifying the SWOT indicators	handy tool for the prompt overview of the current situation in the forest enterprise; construction of other matrices considered as too difficult
BCG matrix	simple and complex interpretation of relations among SBUs in the portfolio; ability to predict the future SBUs positions	only two parameters are considered; unclear by more SBUs and longer time period	easy to use except the graphical output; shows the strengths and weaknesses of the enterprise
GE matrix	deep screening of each SBU position; high expressing power	time-consuming; difficult to gain so many information; only current positions of the SBUs are captured	difficult to realize in every day practice; demanding on input data
ABC analysis	synoptic and undemanding on processing	not possible to estimate the future development; lower expressing power	simple illustration of wood assortments structure according to turnover concentration

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The SWOT analysis is often used also by forest enterprise, but only for the first step of identifying the internal and external indicators. However, this approach minimizes its expressing power. Therefore, it is necessary to conduct this analysis till the end and elaborate all matrices to find out the proper portfolio strategy, company goals for near future.

The contribution of the BCG matrix is in possibility of comparing the SBUs positions in the time period. However, the practical experiences recommend displaying maximum of two or three years depending on number of products due to its limpidity. It is not demanding on input data. On the other hand, GE matrix disposes with the information about the market place, products share on the total market capacity, their attractivity what are the data more difficult to obtain. They require also increased level of objectivity. However, they have excellent expressing power. The contribution of the ABC analysis is in the clustering products into the groups according selected code system. The effect of this approach is in finding of common and different product characters in portfolio. It is important that the clustering rules should underlie the logic, they should have correctly defined boundaries and they must be objective. For clustering codes are usually used following economic indicators, for instance: share on revenues, turnover, market share, the amount of sold products, etc.

The management of forest enterprise looks for the ratio of easiest application versus expressing power in the given supporting methods of decision-making and managing of the product portfolio. Therefore, the SWOT and ABC analysis were accepted by forest enterprise as the most applicable methods or decision-making models.

4. Discussion

The case study results emphasize the possibilities of the combination of selected decision-making models within the marketing management in forestry practices. They build together such a mosaic and supporting tool for the decision-making process. It is necessary to stress out that these models were applied on the forest enterprise what represents a significant particularity within the interpretation of the research outcomes as well as the proposal of the recommendations. Regarding the chosen enterprise, it is a company managing primary the production function of the forests with the aim of its enhancement and encashment (generating the economic profit). Besides the optimization of the product portfolio, the use of these models must bring also the balance between both major targets of the enterprise.

Despite of the product portfolio belonging under the one enterprise, the products compete to each other in some cases inside of the portfolio. It is the example of pulpwood with the fire-wood. Their price levels latent compete (coniferous 21 – 27 € m^{-3}, broadleaves 35 – 39 € m^{-3}) and so confirm this situation reflecting the market environment (Ministry of Agriculture and Rural Development of the Slovak Republic 2018). The increasing demand on fire-wood, or forest chips raised its price on the level of pulpwood what induced this competition also within the product portfolio in the last years. Some heating plants in term of fuel source availability and its price acceded to using also more valuable assortments as the pulpwood or assortments of III. qualitative class for heat production as the consequence. Behind this state was the binding target to increase the share of energy from renewable sources in final consumption of energy and hereby the strong support of green energy by state government in form of high feed-in tariffs (Commission of the European Communities 2008).

This adjustment of the green energy support incurred deformation also on the market with roundwood assortments. Therefore, there is a trend to decrease the feed-in tariffs or change into the feed-in premium, however, not in combined production of electricity and heat (309/2018 Z. z.). Despite of the boom in demand on energy wood, the production of fire-wood as well as forest chips is ineffective for the chosen state forest enterprise. The fire-wood from thinning is sold to the locals for symbolic price or it is outsourced for forest chips production right next to the forest stand. In general, it depends on availability of wood material (forest road network, the level of forest stand access) and its concentration in the given locality.

Practical application of marketing decision-making models on the forest enterprise has its own particularities. There are several reasons e.g. (Brunette et al. 2015; Rymanov 2017): i) long production (rotation) period, ii) increasing occurrence of natural hazards, iii) wood processing technology, iv) differential land rent, etc. In this case study, the recommendation of marketing approach for managing the forest enterprise is to focus on the pillars of the product portfolio and to develop them. Concretely, it is concerned of increase roundwood assortments whereas III. qualitative class is the most treasured assortment regarding the ratio of its price and available amount on the market. Because there is a very few processing companies of I. and II. qualitative class (mainly for broadleaves processing, shortage of veneer mills, furniture companies), it is very implausible that forest enterprise could place a huge amount of these assortments on the domestic market (Paluš et al. 2015). One of the options is to export these assortments with the possibility of better economic assessment. Hence, the reference is to apply the diversification strategy for sales management. The next recommendation is not to break with the manipulation of the whole trunk length on individual assortments even by the forest stand. The forest enterprise loses the added value with this approach. Further, it is necessary to provide some own harvesting activities with own vehicles in comparing with outsourced force on the forest enterprise. The reasons behind are several due to the continuous processing of roundwood and its

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deliveries on the market, for instance: i) unreliability from one of the contractors, or ii) occurrence of accidental felling where by long public tenders for contractor the forest enterprise often loses profits (Paluš et al. 2011).

It is necessary to put the attention on the oversize product portfolio with the III. class assortments mainly coniferous. It is the effect of the forest management in Europe initiated by demand on economic effective wood species (spruce) from the 19th century to the end of the first half of 20th century. This approach lead to weak biodiversity of the local ecosystem. However, this state is nowadays by bark beetle calamity, climate change, considerably risky. Therefore, it is essential to substitute e.g. spruce (Table 1) by natural wood species like beech or fir (Carpathian mixture) in the given locations and gradually increase the share of mixed forest as well as the biodiversity.

The methodological reference for chosen forest enterprise is to supplement the ABC analysis by the analysis of the contribution to the fixed costs and so to increase its expressing power. Then, it will be necessary to account the structure of individual costs items for each roundwood assortment. The reason is that although strong products with the biggest share on the total sales need not to have a marked profit, or they can be even loss (Kádárová et al. 2015).

Based on the experiences with the application of the given marketing decision-making models into the praxis we can state following conclusions. By using the decision-making models, the scope of the market size depends on the size of the surveyed enterprise, type of the sector related to the examined company, character of the offered product or service, type of the target customers as well as available data (Evans & Berman 1990). In the most cases, the marketing decision-making models are used at the regional or national level. However, concerning the transnational corporations disposing with enough data quantity (Baum 2012), they keep under review the positions of their subsidiaries on the global level, or in individual world regions (e.g. EU, Asia, North America etc.).

Chosen decision-making models serve mostly for the proposals of the managerial solutions in the short-term perspective for one or maximum two years, as well as within the operative planning. They are only supporting methods or approaches for the strategic decisions. They follow the actual situation on the markets and in the company portfolio. On the other hand, they are not the regular tools for the predictions. Their application for the goods of the commodity markets (behave on the principle of the derived demand) needs a precise interpretation of the results due to a lot of specifics coming from the character of the given markets (Kotler & Keller 2015). However, within the marketing management of the forest enterprises portfolio the use of these models into praxis is an innovative approach of the forest resources management. It increases the competitiveness of forest enterprises, and their resistance against market changes. It optimizes their company portfolio and supports the quality of decision-making (Hansen & Juslin 2011).

5. Conclusion

In consequence of the conducted case study, marketing management of the forest products portfolio is necessary. The decision-making process requests the combination of several viewpoints. The methods of marketing decision-making models can be applied in managing of forest enterprise and they are a great contribution. However, the important are the experiences, and knowledge of the marketer or manager for the correct interpretation of the results by individual matrices.

From the results, the forest enterprise is focused on the production of III. qualitative class of roundwood assortments (broadleaves and coniferous) as well as broadleaf pulpwood. This state outcomes from the condition of the forest land reserves where the forest enterprise operates as well as from the structure and current situation on the wood-processing, pulp and paper and furniture industry, also energy policy at the national and at the EU level.

Acknowledgment

The author is grateful for the financial support of the two projects at the Slovak Research and Development Agency (APVV-15-0715), (APVV-17-0232) and APVV-18-0520.

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Cent. Eur. For. J. 65 (2019) 233–244 sciendo DOI: 10.2478/forj-2019-0019

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ORIGINAL PAPER

Multi-objective land allocation for zoning of ecosystem services in mountain forests

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Abstract

The paper proposes a system for zoning of mountain areas based on the level of provisioning of ecosystem services. Techniques of multi-objective land allocation were applied to allocate complementary and conflicting objectives. The zoning system consists of four phases: i) Identification of criteria for the evaluation of ecosystem services; ii) Quantification of criteria for three different forestland states; iii) Evaluation of potential and effect of the forest on providing the ecosystem services and iv) Zoning of ecosystem services with their prioritization and spatial allocation of support measures. The study was conducted in the Tatra Mountains (Slovakia). Erosion control, avalanche control, wood production and cultural services were evaluated. The greatest differences between potential and effect of the evaluated ecosystem services were identified for the avalanche control. A comparison of our results with the existing (control) map of ecosystem services has proved that the proposed system is a potent means for multi-objective forest planning.

Key words: decision support; ecosystem services; fuzzy logic; mountain forests; multi-objective land allocation

Editor: Tomáš Hlásny

1. Introduction

One of the topical tasks of the present is the sustainable management of natural resources. In forest landscapes, we observe an increasing demand on various provisioning, regulating, supporting and cultural ecosystem services such as quality and quantity of fresh water, wood as a renewable source of energy, mitigation of natural disaster consequences such as flooding, drought, avalanches, landslides, increasing demand on recreation in the forest etc. The concept of multi-objective forest planning is suitable on satisfying such a wide range of alternatives (Pukkala 2010).

Origin of the multi-objective (multiple-use) concept can be found in Germany and the USA. The concept has been developing from the 1960s in Nordic countries too (Hytönen 1995). Depending on the tradition of forest management, natural and socio-economic conditions, two main approaches can be distinguished: the segregation and integration approach (Boncina 2011). The segregation approach is preferred by countries with large forest areas and low population density (e.g. Canada, Russia). Multiple objectives are achieved on a larger scale by dividing the forests to areas with single but different uses. In Central Europe, the integration approach was preferred. That approach maintains more uses at the same time and in the same forest area. The importance of particular objectives can be different, but unlike the segregation approach, the most important objectives do not exclude others, not even conflicting objectives. Those are only given a lower priority and trade-off are evaluated.

The methodology of Papánek (1978) is among the first ones in Central Europe representing a practical handbook for forest managers on how to incorporate the integrated approach to forest planning. The author introduced methods for designation of forest areas with different prioritization of ecosystem services (e. g. category of the forest, functional type and spectrum, management designation of the forest). Simoncic et al. (2013) consider as an important part of the integration approach the designation of priority areas, which are relatively more important for selected objectives than forests outside of these areas. Priority areas are used as a general term for areas where selected ecosystem services (goods, benefits, functions) play important role in multi-objective forest planning. The latter authors distinguished two main types of priority areas widely used in the Central European forestry: forest function areas (zones for selected ecosystem services) and protected areas. The authors discuss some crucial reasons why priority areas are used in forest planning:

– Priority areas are an important tool for differentiating management objectives and measures within large forest areas (Bettinger et al. 2009)

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- Priority areas are an important for public participation and forest sector cooperation in spatial planning (Betteliny et al. 2000; Kangas et al. 2010)
- Priority areas provide a spatial framework for allocation of financial compensations and subsidies and can therefore be a useful tool for the implementation of forestry policy (Cubbage et al. 2007).

Participation of various stakeholders in multi-objective planning highlights the need of evaluation of numerous management alternatives and requires the utilizing of up-to-date tools and methods for objective and transparency designation of priority areas. In multi-objective forest planning, forest plans are evaluated using various multicriteria decision methods and multi-objective optimization algorithms (Pukkala 2010). An extensive overview of decision support tools to operationalize the ecosystem services concept presents Grêt-Regamey et al. (2017). Nine state-of-the-art European forest decision support systems (DSS) focused on ecosystem services provisioning at the landscape scale were assessed by Nordström et al. (2019). Reynolds et al. (2008) divides optimization techniques used in decision support system into three general classes:

- Multicriteria decision models
- Artificial neural networks
- Knowledge-based systems

Multicriteria decision models help to structure complex decisions in forest management by decomposing multiple objectives to relatively simple, measurable criteria. Such an approach brings a transparent and comprehensive way for comparison various alternatives especially in DSS with public participation.

The advantage of Artificial neural networks (ANN) is that it facilitates analysis of the more qualitative aspects of the decision-making process. The necessity of large data set for network training and testing purposes have some limitations in forest management. Another limitation on the use of ANN arises from the complex mathematical nature of this technique, which often causes it to be a black box. This worsens the explanation capabilities of the results to the end user.

On the other hand, the architecture of knowledge-based systems (KBS) make those systems a white box, and therefore they have become more successful in addressing forest management issues. The main feature of KBS is to make decisions about the system based on knowledge of its behavior while system behavior is formalized in knowledge base by expert. Derived conclusions are presented in relatively simple and intuitive terms and thus enables to involve potentially many managers, scientists and stakeholders into the decision process (Reynolds et al. 2008).

For the tasks of multi-objective optimization and spatial allocation of priority areas play the very important role analytical tools of GIS. They enlarge DSS into spatial decision support systems (Tuček & Sitko 2000). In the case of complementary objectives there are used ranking procedures based on results of the multi-criteria evaluation. In case of the task of multi-objective land allocation under conditions of conflicting objectives clear priorities cannot be set. Mathematical programming solutions can work quite well in instances where only a smaller number of alternatives are being addressed. However, in the case of huge GIS raster data sets and many management objectives involvements, the choice of heuristic methods is more appropriate (Eastman 2016).

To our knowledge, the approach integrating analytical tools of GIS and DSS for zoning of ecosystem services in Central Europe mountain forests is missing. The aim of the current study is therefore to (1) propose the workflow for solving the complex multi-objective land allocation tasks using a scientifically sound and practical approach and (2) demonstrate precise zoning of priority areas and spatial allocation of measures that support respective ecosystem services (support measures). We consider in this study both complementary and conflicting objectives typically occur in the Central European mountain forests.

2. Materials and methods

2.1. Model territory

The model territory is a catchment situated in the highest mountain range of the Carpathians, the Tatra Mountains (Fig. 1). In 2004, around 12,000 ha of forests were completely damaged due to windthrow. In next 5 years, other 1,545 ha of forests died due to a bark beetle outbreak (Nikolov et al. 2010). A part of the devastated forests is located in the model territory. The size of the territory is 2,493 ha. Its valuable biotopes and areas are included in the European network of protected areas NATURA 2000. The territory has a high-mountain character with a rugged terrain relief with altitudes ranging from 1,100–2,052 m a.s.l. The long-term average air temperature varies from 0.2 to 4.4 °C depending on the altitude, in vegetation period (May–August) from 6.6 to 11.9 °C. The long-term annual sum of precipitation is 1 485 mm. The site is predominantly made up of metamorphites. Cambisoil occurs in the lowest altitudes, followed by podsols, and in the highest altitudes, the groups of ochric soils can be found. Phytosociologically, in the model area predominates the associations Sorbeto-Piceetum and Cembreto-Piceetum which continuously pass to Cembreto-Mughetum and to acidic associations of Mughetum acidofilum. Norway spruce is dominant, covers 32% of the territory. Mountain ash (19%) and Swiss stone pine (5%) are admixed and European larch occurs only rarely. The dwarf pine above the timberline covers 7% of the territory. The rest of the territory (47%) is covered by grassland or is not covered with vegetation.

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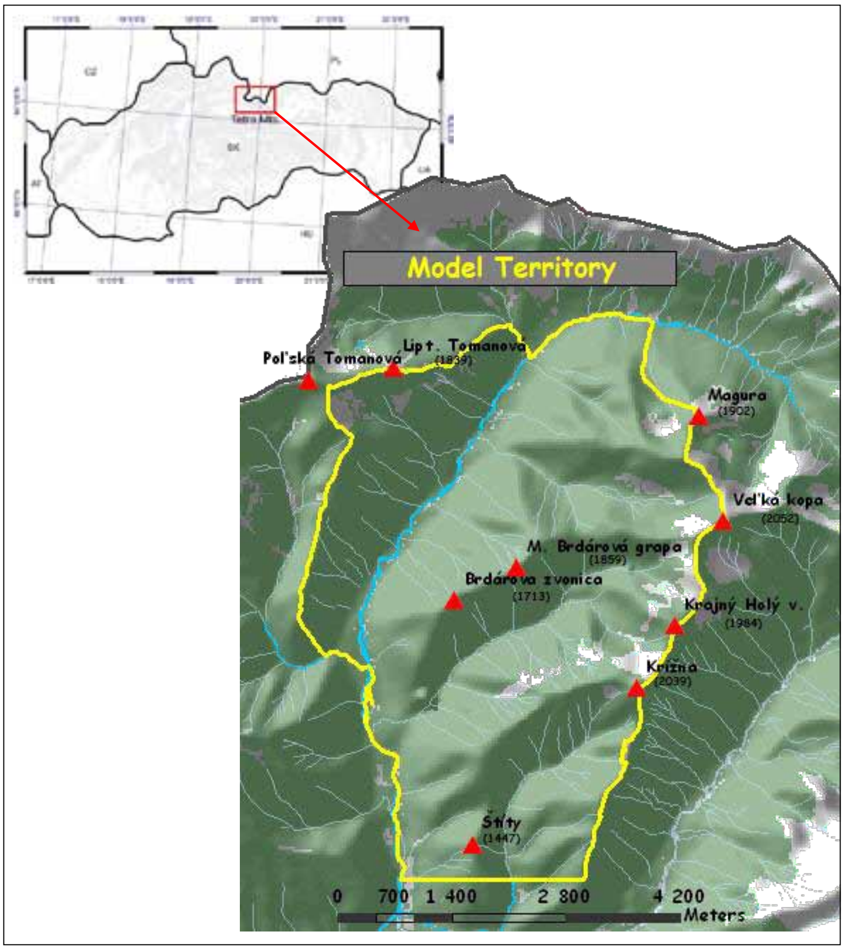

Fig. 1. Location of the model territory (yellow borderline) in the Tatra Mountains (located in the red rectangle), Slovakia (SK). The shaded slopes with runoff channels (white lines) and permanent stream (blue line). Green areas represent the forest stands with any tree/dwarf pine cover, white/grey areas the stands without any tree/dwarf pine cover. Elevation is displayed in the parenthesis.

2.2. Data sources

The investigated ecosystem services were: avalanche control, erosion control, wood production and cultural services of the forest. The group of cultural services is related to the preference of nature conservation in the model territory. By favoring that objective, the forest provides multiple cultural ecosystem services, e.g.: recreation, spiritual and aesthetic values, mental and physical health etc.

The following data sources were used:

- digital elevation model (DEM)
- geological and pedological maps (Landscape atlas of the Slovak Republic, 2013)
- classification of vegetation cover from IKONOS satellite data (Scheer & Sitko 2007a)
- map of avalanche tracks (provided by Center of Avalanche Prevention, Slovakia)
- map of protected areas (provided by Slovak Environment Agency)
- map of management group of forest types (provided by National Forest Center, Slovakia)
- map of forest compartments (provided by National Forest Center, Slovakia)
- data from the forest management databases (provided by National Forest Center, Slovakia)
- climatic data from meteorological stations (provided by Slovak Hydrometeorological Institute).

2.3. Workflow for the allocation of priority areas

The term "priority areas" is used for designating areas under specific management objectives and setting spatially defined management priorities in nature conservation planning (Simoncic et al. 2013). The result of the here proposed workflow is zoning of priority areas, based on:

- mapping of spectrum of ecosystem services, which express the potential of forest to provide selected services
- spatial allocation of measures that support respective ecosystem services (support measures), in areas with

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the greatest difference between potential and effect of the forest on providing the services

We use multi-objective optimization techniques implemented in GIS for allocation of land for the specific objectives. This is preceded by process of evaluation of ecosystem services. The knowledge base was formalized for evaluation of potential of forestland for provision of ecosystem services (hereinafter called service potential) as well as service effect, which characterize actual provision of ecosystem services. The proposed workflow consists of four consecutive phases (Fig. 2).

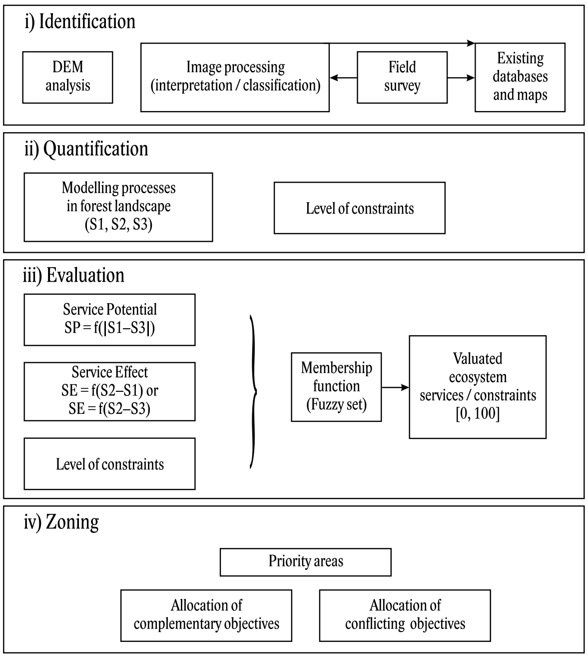

Fig. 2. Scheme of the proposed workflow for evaluation of ecosystem services and allocation of priority areas: i) Identification of criteria important for evaluation of ecosystem services; ii) Quantification of criteria for three states of the forest – optimal (S1), actual (S2) and extreme (S3); iii) Evaluation of potential and effect of the forestland with providing the ecosystem services – identifying differences between scenarios and transforming them through defined membership functions to truth values 0 – 100 (0 – no potential/effect of service, 100 – the highest potential/effect of service); iv) Zoning of ecosystem services with their prioritization and allocation of support measures for complementary as well as conflicting objectives.

i) Identification of criteria – phase aimed to choosing the criteria important for the assessment of ecosystem services. The selection of criteria is closely linked to the method of their quantification in the next phase of the workflow.

Criteria for evaluation of **soil protection** services: rainfall and runoff; soil erodibility; altitude, inclination, shape and length of slopes; overall slope of avalanche tracks; contributing area; density and type of vegetation cover.

Criteria for evaluation of **wood production** service: index of the reduced growing stock level; stocking; the proportion of the assortments of I.–III.A assortment class; coefficient of slenderness; total mean value increment.

Important requirement is exclusion of wood production from prioritization for areas designated for nature conservation which leads to support **cultural** ecosystem services.

Geoinformatics technics such as DEM analysis, spatial interpolation, tree species classification and identification of avalanche tracks based on image data were utilized to update and enhance the existing databases and maps. The field survey was realized to gain auxiliary data for supervised classification of tree species composition.

ii) Quantification of criteria – modeling of the soil erosion, avalanche processes, wood production in technical units and with the various influence of the forest structure as well as specifying the level of constraints resulting from nature conservation objectives, were performed. In order to be able to evaluate both the potential and the effect of fulfilling ecosystem services in next phase, quantification of the criteria was done for the following three scenarios:

- optimal state of forest (S1) characterized by natural altitudinal occurrence of tree species and by typological classification of the territory into management groups of forest types;
- real state of forest (S2) given by the actual state of forest stands;
- extreme state of forest stands (S3) with no trees at the stands.

Quantification of **soil erosion** for all three scenarios was based on the semi-empirical model MUSLE (Moor & Wilson 1992). The model quantifies the average soil loss in tons per hectare per year. S1 scenario expresses minimum soil loss modeled in the model territory, scenario S2 actual erosion, and S3 scenario is considered as maximum soil loss.

Quantification of criteria for evaluation of **avalanche control** is based on identification of avalanche trigger zones and modeling maximum runout distance of avalanche tracks. Maximum avalanche runout distance was modeled by Alfa-Beta empirical model (McClung & Mears 1991). The expert system of the identification of avalanche trigger zones was developed in collaboration with the Avalanche Prevention Center, Slovakia. The system quantifies the plausibility of avalanche triggering based on the assessment of three groups of factors: climatic, topographical and land cover. Runout distance of avalanche tracks was modeled for all potential trigger zones identified assuming no action of trees in S3 scenario as well as optimal tree composition in S1 scenario. S2 scenario reflects actual occurrence of avalanche tracks recorded in map of avalanche tracks updated utilizing Ikonos satellite data.

Real **wood production** of the forest (S2) is assessed based on four criteria quantifying the quantity, quality, and safety of wood production. The wood production for optimal state of the forest (S1) was quantified based on the results of simulation using the semi-empirical tree growth simulator Sibyla (Fabrika & Ďurský 2006). The

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simulation was processed for the plots representing management groups of forest types occurring in model territory. Total mean value increment (TMVI) was quantified in Eur per hectare. In the case of the extreme state of the forest stand (S3), we expect no wood production.

Criterion for **cultural** services was quantified by a degree of the territorial protection from 1 to 5 (1–the lowest, 5–the highest degree), as defined by the national legislation. However, quantification was not performed for all three scenarios. Constraints arising from nature conservation issues have at the whole model territory the high importance because the whole area is in a long-term under the 4th or the 5th degree of territorial protection and there are situated sites protected by the NATURA 2000 too. Therefore, we simplify the quantification procedure by assuming that the value of the criterion used for the optimal state (S1) and the actual state of the forestland (S2) is identical.

iii) Evaluation of ecosystem services – in order to compare various ecosystem services and assess the uncertainty in the evaluation process, the evaluation concept utilizing the fuzzy logic was applied. As a main tool of the evaluation, the membership function is defined. The function is created by expert experience. The domain values of the function are formed by the quantified criteria, measured in technical units or by the indexes without any units (e.g. t ha^{-1} $year^{-1}$, m^3 ha^{-1}, degrees etc.). Those are transformed into a continuous-valued metric, known as the truth value (Reynolds & Hessburg 2005). Truth value expresses the degree of support for proposition that the respective criterion or ecosystem service has the highest importance of all evaluated services. We use interval of truth values [0, 100], where 100 represents the highest importance of ecosystem service. Two general features of ecosystem services were evaluated:

– Service Potential (SP) – potential of forestland for provision of ecosystem services; membership function is defined for domain values derived as the absolute difference between quantified scenarios S3 and S1. The greater absolute difference between scenarios means the greater service potential (e.g. greater difference of maximum soil loss for no forest cover (S3) and minimum soil loss controlled by optimal forest (S1) means greater erosion control potential):

$$SP = f(|S3 - S1|)$$

– Service Effect (SE) – actual provision of ecosystem services; membership function is defined for domain values derived as the difference of quantified scenarios S2 and S3 or S1. The greater the difference between scenarios, the greater the service effect (e.g. greater difference between actual soil loss modeled for actual forest (S2) and minimum soil loss modelled for optimal forest (S1) means greater erosion control effect):

$$SE = f(S2 - S1), \text{ if } S1 < S3$$

$$SE = f(S2 - S3), \text{ if } S3 < S1$$

The development system for knowledge base NetWeaver was used to define the membership functions. It is embedded in the EMDS (Ecosystem Management Decision Support) software (Reynolds 2013). The system provides decision support for landscape-level analyses trough logic and decision engines integrated with ArcGIS software (ESRI 2011).

The approach used for membership function creation we describe on the evaluation of the **erosion control** service of the forest. The membership function was determined according to the expert knowledge of tolerable or compensated erosion. The function (Fig. 3) starts from the level of tolerable soil loss, 7.5 t ha^{-1} $year^{-1}$ (Šály & Midriak 1995). The membership function is rising from that point steeper until the breakpoint of 22.5 t ha^{-1} $year^{-1}$. It is considered as a boundary between moderate and severe soil loss by the last cited paper. The forestland which can prevent the soil loss above or equal to 75 t ha^{-1} $year^{-1}$ reaches the highest truth value (100). The same function was used for evaluation SP as well as SE.

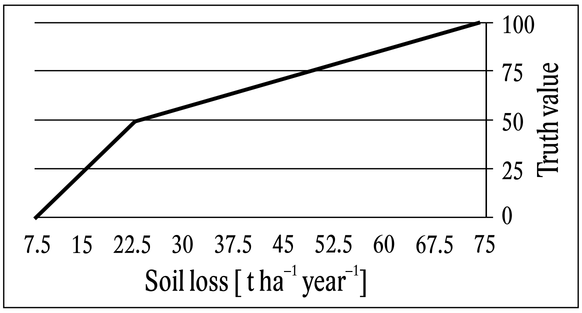

Fig. 3. Membership function for evaluation of the erosion control service of the forest.

The knowledge about the parameters of avalanches, which a forest might halt (secondary avalanche control service), or what type of forest is able to prevent the avalanche trigger (primary avalanche control service) were formalized to knowledgebase for evaluation of the **avalanche control** service of the forest (Sitko & Scheer 2013). The 13 membership functions and 3 constant values were established for 9 criteria and the final value of the respective service was performed on basis AND aggregation by minimum-biased weighted average (Reynolds et al. 2002).

A similar approach of multicriteria aggregation is also used at the evaluation of **wood production**. The structure of knowledge base created for evaluation of wood production SE shows logic diagram (Fig. 4).

Domain values of stocking are used for evaluation of production area utilization. The productivity of stand is evaluated based on values of the index of the reduced growing stock level (Ired). Percentage of the assortments of I.–III.A assortment class formed domain values of membership function for evaluation of the quality of production and by the coefficient of slenderness (H/D ratio) is evaluated the safety of production. Breakpoints of membership functions for all criteria used for evaluation wood production service summarize Table 1.

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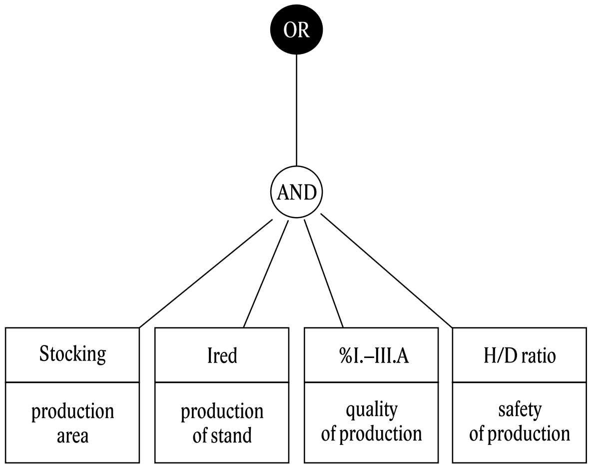


Fig. 4. The knowledge base for evaluation of wood production effect of the forest (I_{red} – index of reduced growing stock level, %I.–III.A – the proportion of the assortments of I.–III.A assortment class, H/D ratio – coefficient of slenderness).

Table 1. Parameters of membership functions used for the evaluation of wood production.

Criterion	Breakpoints of membership functions					Reference
	0	50	100	50	30	
Stocking	0.1	0.4	0.7–0.9	1.3	—	Fabrika (2006)
Ired	0.10	0.55	1.00	—	—	Scheer & Sitko (2007b)
%I.–III.A	0	20	40	—	—	Fabrika (2007)
H/D ratio	—	—	0.00–1.00	1.71	2.00	Fabrika (2007)
TMVI*	167	334	668	—	—	Papánek (1978)

Ired – index of the reduced growing stock level; %I.–III.A – the percentage of the assortments of I.–III.A assortment class; H/D ratio – coefficient of slenderness; TMVI – total mean value increment in € ha^{-1}, prices actualized in 2009, *used just for the evaluation of wood production potential.

The value of **cultural** ecosystem services assigned for various levels of nature conservation presents Table 2. Biotopes and areas included to NATURA 2000 receive the highest value 100 as does the fifth degree of territorial protection. Since not all three scenarios have been quantified, cultural SP and SE were evaluated at the same level.

Table 2. Value of cultural ecosystem services assigned for 5 degrees of territorial protection.

Degree of territorial protection:	1st	2nd	3rd	4th	5th
Truth value of cultural services:	10	40	70	90	100

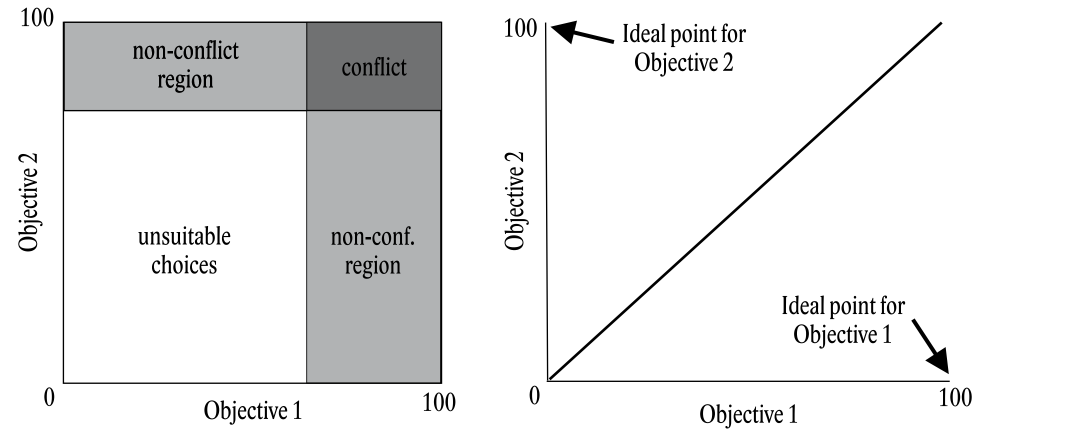
The output of this phase is the creation of a suitability map (SM) for every evaluated SP and SE of ecosystem services. Four levels of importance of ecosystem services are distinguished:

– negligible – truth value less 10
– low – truth value within 10 – 39
– medium – truth value within 40 – 69
– high – truth value equal to or higher than 70

iv) Zoning of priority areas – is the final phase of the proposed workflow and includes the mapping of the spectrum of ecosystem services (SES). It is processed by the cross-classification procedure on individual SMs.

The allocation of support measures for valuated ecosystem services is based on an integrated approach to multi-objective forest planning. The proposed system allows to integrate multiple complementary objectives as well as conflicting ones. The procedure follows up the previous phase by finding out the difference between SP and SE. The greatest differences are represented by the sites with the highest disproportions between the potential and the real fulfillment of the investigated ecosystem services. The allocation of support measures for complementary services rests in the choice of territories with the highest disproportions. Ranking procedures built in the GIS software Idrisi (ClarkLabs 2012) have been used.

For the services with conflicting supporting requirements, the Multi-objective Land Allocation procedure (MOLA) was applied (Eastman 2016). This procedure allocates multiple conflicting objectives on the basis of the iterative reassessment of the score (SP–SE differences) in the conflicting zone until the defined area requirements are fulfilled (Fig. 5). The result of this



(a) (b)

Fig. 5. The decision space formed by treating suitability values for each objective as a separate dimension. (a) The decision lines isolating the best regions to meet areal goals for the objectives, in the case of two objectives their intersect forms four regions: two regions of choices desired by one objective and not the other (and thus not in conflict), a region of choices not desired by either, and a conflicting region of choices desired by both; (b) The conflicting region is iteratively partitioned between objectives by means of a minimum-distance-to-ideal-point logic that partitions the decision space with a line whose angle is determined by the relative weight assigned to the objectives (modified according to Eastman 1995).

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procedure is finding a trade-off solution bringing about suitability optimization of the territory utilization to fulfill the defined objectives.

3. Results

Proposed four-phase workflow of the evaluation ecosystem services and zoning of priority areas was applied for evaluation of the potential (SP) and the effect (SE) of selected ecosystem services provided by the here investigated mountain forest. Separate subchapters bring results about mapping of the spectrum of selected ecosystem services (SES) and allocation of support measures for complementary as well as conflicting objectives in the model territory.

3.1. Erosion control

Evaluation of the erosion control has shown that the majority of the model territory has high SP. The resulting truth values of the service in the map of the suitability (SM) for erosion control potential have reached mean value 95.9 for the entire model territory. Distribution of values is given in the histogram (Fig. 6a). Variation of the service value is only 14%, which refers to rugged terrain and a high slope inclination in the majority of the entire region. Mean slope inclination in the model territory is 29°.

SE quantified by the model MUSLE points out the fact that a real fulfillment of the erosion control service is on an acceptable level (Fig. 6b). The mean value of the service is 91.5 and the coefficient of variation increased to 24%. It depends on a different state of vegetation cover in the model territory. Higher values of soil loss were found in terrain furrows, where the surface water flow is accumulated to gully and tree cover in these places is usually destroyed as a result of avalanche activities. On these sites, the greatest difference between the erosion control potential and effect of the forest has been found. A dominant part of slopes below the timberline is covered by forest stands which, in a suitable way, eliminate deleterious effects of water erosion.

The results obtained by its application in the forest management unit High Tatra were tested against the terrestrially measured values of soil loss. A high correlation between the measured and the modeled values has been found, and the coefficient of determination reached the value of 0.82. Systematic overestimation of modeled results was corrected with a two-phase sampling by using a correction coefficient with a standard error of ±22.6%.

3.2. Avalanche control

The 452 ha (29%) of forest stands with a truth value over 70 were classified into a category with the high avalanche control SP. However, a real fulfillment of the avalanche control service on the respective level is secured only by 114 ha of forest stands. This disproportion is obvious from the comparison of histograms in Fig. 7a, b. In summary statistics of avalanche control effect of the forest, this was expressed by a decrease in the mean truth value by 12 in comparison to avalanche control potential. This difference suggests that there are reserves in fulfillment of the avalanche control service. These results are, however, biased by database uncertainty, i.e. errors of the input data. A certain underestimation of the resulting SP arises from classification results of vegetation cover from the IKONOS images. Within this classification, the proportion of rowan occurrence was overestimated by 3.6% at the expense of conifers, which have a better avalanche control effect. This was manifested by a lower value of SE.

Model parameters used for the quantification of the maximum run-out distance of avalanches in the model territory are very favorable. The coefficient of determination reached the value of 0.98, and the mean error of the model is ±1.12°.

3.3. Wood production

Wood production service was evaluated at two scales. Wood production potential was evaluated for management groups of forest type (MGFT) and wood production

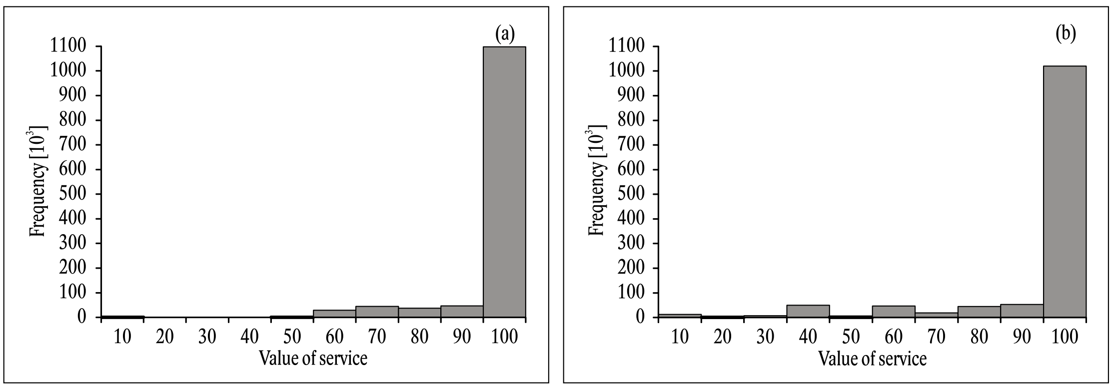

Fig. 6. Distribution of truth values of (a) erosion control potential, (b) erosion control effect of the forest.

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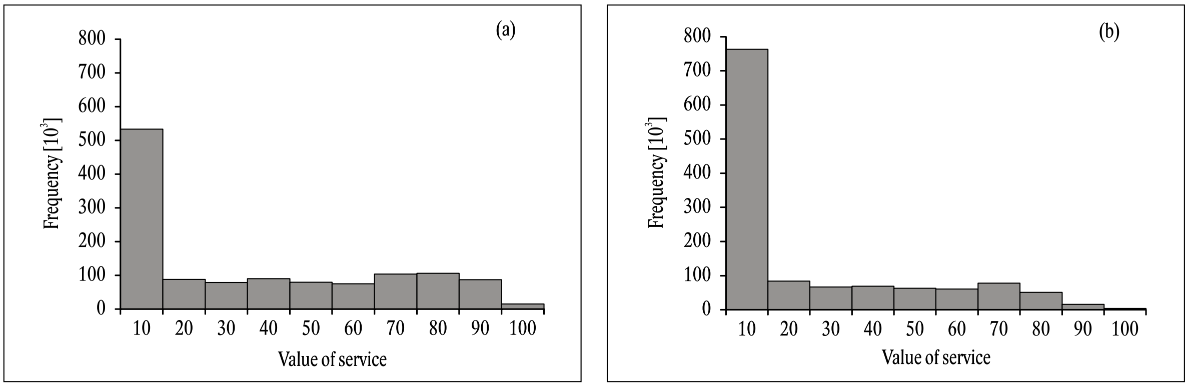

Fig. 7. Distribution of truth values of (a) avalanche control potential, (b) avalanche control effect of the forest.

effect for forest stands (compartments). SP of the whole model territory has the mean truth value 12. Excluding the sites over timberline the mean value increased to 33. Distribution of the values is given in the histogram (Fig. 8a). Real fulfillment of wood production service was evaluated by the mean value of SE 8, for the stands under timberline it is 22. From the comparison of the distribution of wood production potential at Fig. 8a and effect at Fig. 8b, it can be seen disproportion, which can result from different scales used for evaluation SP and SE. Forest stands, in the evaluation of wood production potential were grouped into three categories of MGFTs. The highest frequency (68%) has the category with the negligible wood production potential. The value of the service is up to 10 with dominance the sites over timberline. 23% of model territory is covered by forest stands under timberline with low production potential, 1 % of forest stands have middle and 8 % have high production potential. Frequency of the production effect is more continuous decreasing as it can be seen in Fig. 8b. Low wood production effect was evaluated by 25% of the model territory, middle effect by 1% and the high production effect has been evaluated less than 1% of the model territory. The rest of the entire territory (73%) has negligible production effect, where dominate area close to or over the timberline, and partially area damaged by avalanches and wind-throw.

3.4. Zoning of priority areas

Finally, the evaluated ecosystem services were zoned over the model territory. The map of SES was created from suitability maps of SP. The combinations of three levels of the SP are expressed by numerical codes (Fig. 9).

Most frequently occurring priority area is 1–1–0. This code defines a zone in which the cultural services have high priority (**1–**1–0), and also the soil-protection potential reaches a high level (1–**1–**0). The wood production potential is on a negligible level (1–1–**0**) in those sites. The area of the respective zone is 1270 ha (51% of the model territory). Zone 1–1–3 makes up 35% of the total area. Except the services mentioned above, a low wood production potential occurs in this zone. Another 9% of the model territory within the zone 1–1–1 has high production potential and high culture and soil-protection potential. Other zone with a proportion higher than 1% is a zone 1–2–1 with an area of 75 ha. It is the zone with a medium soil-protection potential.

The allocation of support measures for complementary objectives was aimed at soil-protection, particularly increasing the avalanche control effect of a forest. As for the conflicting objectives, the allocation of support for wood production service and avalanche control service of the forest was carried out. This was done in spite of the fact that the utilization of production potential is not considered in the model territory because of nature con-

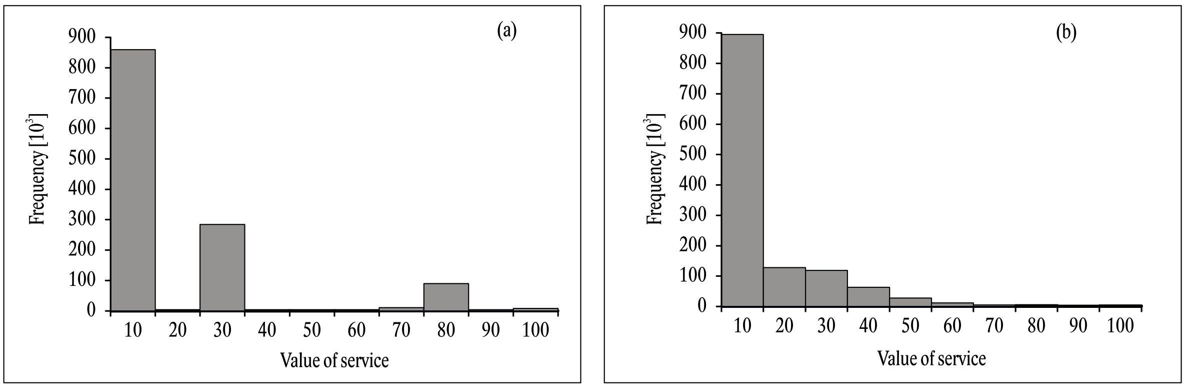

Fig. 8. Distribution of truth values of (a) wood production potential, (b) wood production effect of the forest.

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servation concerns. The aim of such allocation is to point out the versatility of the proposed workflow.

3.4.1 Allocation of complementary objectives

Based on the mapping of SES (Fig. 9), the cultural, avalanche control, and erosion control services were chosen as the priorities in the model territory. All of them are characterized by similar supporting measures, we therefore treat them as complementary objectives. As the evaluation phase suggested, the most notable gaps in the utilization of SP has the avalanche control. The requirement for the improvement of this service was estimated for a forest area of 200 ha and the measures were suggested to be taken in the sites with the highest avalanche control potential (Fig. 10a). Green areas represent an area of 200 ha in which the greatest differences between the evaluated avalanche control SP and SE were found. Adequate support measures can increase the avalanche control most efficiently in this area.

3.4.2 Allocation of conflicting objectives

The avalanche control and wood production service are considered here as conflicting objectives. Conflict is based on the incompatibility of the supporting measures these services when applied at the same site. The technique of the iterative re-evaluation of the conflicting zone has been used for the allocation of compromise solutions by means of the MOLA procedure. The following input parameters have been set:

– area requirements for the allocation of supporting measures for ecosystem services
– map layers with values of differences between SP and SE for allocated services
– SM evaluating SP for allocated services
– weights determining the relative proportion that each objective will have in resolving conflicting claims for land (this value can reflect for example the proportion of costs to reach the conflicting objectives)

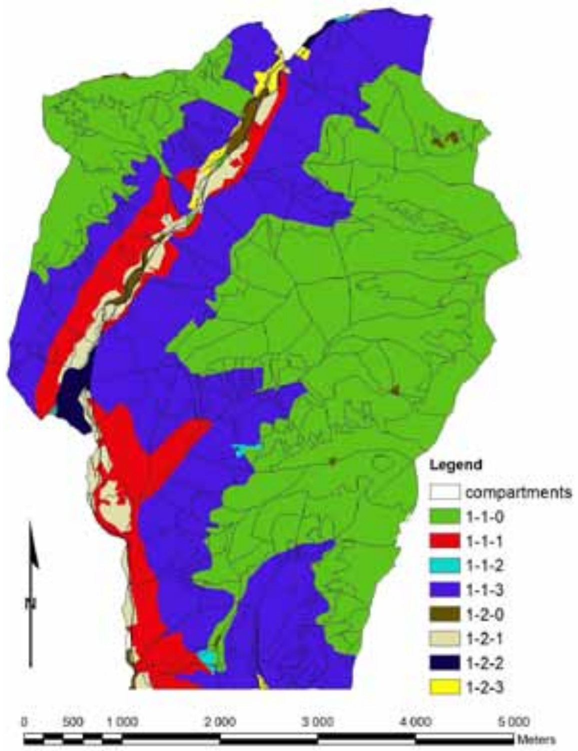

Fig. 9. Map of the spectrum of ecosystem services. Code 1 represents the high SP, 2 medium SP, 3 low SP and 0 negligible SP, in order: cultural–soil protection–wood production.

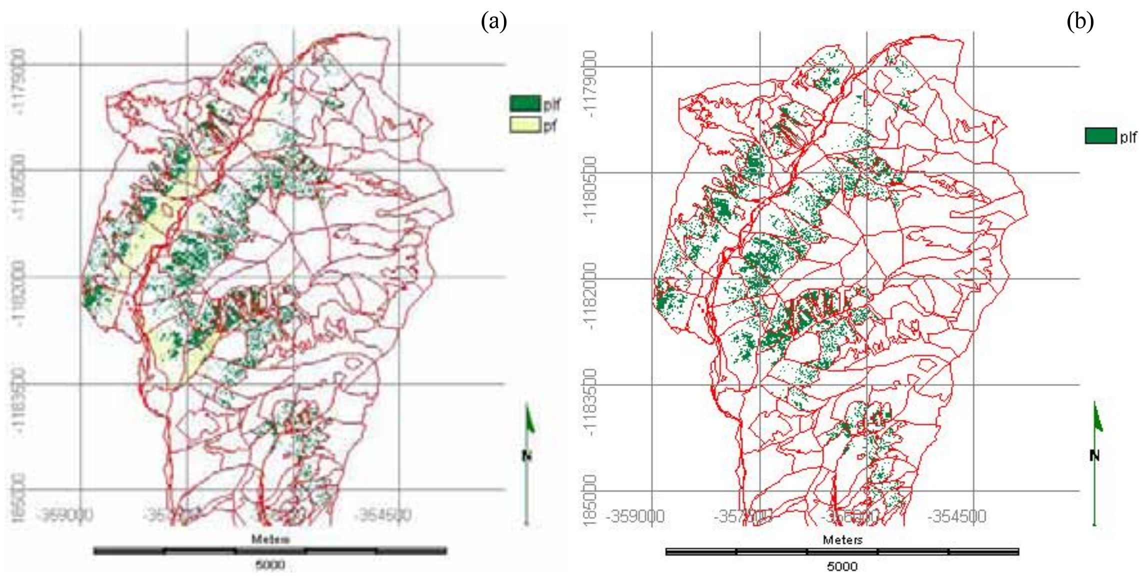

Fig. 10. Allocation of support measures for (a) complementary objectives (cultural, avalanche control and erosion control ecosystem services) to support the avalanche control service (acf); (b) conflicting objectives with compromise solution for avalanche control and wood production (pf).

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The real requirement for the support of the avalanche control service remained unchanged (200 ha) and that for the wood production represents 72 ha. The allocation of support measures aimed at sites with the high soil-protection and wood production potential. The SM of the avalanche control and wood production potential were used as auxiliary data optimizing the decisions in the conflicting zone. The maps were used for rectification of the allocation of the avalanche control service in places, where the production potential is the lowest one. A similar procedure was also applied for the production service. The equal importance (weight) was considered for both objectives.

The allocation result is shown in Fig. 10b. When comparing the allocated areas with the area chosen for support measures in the previous task, it has been found that an area of about 10 ha, where measures supporting the avalanche control we proposed to be taken, was within the compromise solution assigned to support of the wood production service. There was no significant spatial conflict of interests, which is also related to the character of both services. Production potential has been evaluated as the highest one in the valley of the model territory and the avalanche control service has been evaluated as significant in forest stands below the timberline and in the middle part of the slopes.

4. Discussion

Term priority area as a general term for areas where the ecosystem services and their priorities are important indicator for multi-objective forest planning brings Simoncic et al. (2013). This concept fits well into the proposed workflow of zoning of ecosystem services. The spectrum of ecosystem services (SES) was mapped in the model territory. SES reflects the diversity of services provided by the forest ecosystem, but also their importance (priority). It is an appropriate characteristic to differentiate objectives and measures within large forest areas and can be a spatial framework for planning possible financial compensations and subsidies for supporting of ecosystem services.

Intuitive expression of SP and SE by the truth values in the interval [0, 100], as well as transparency in the formalization of the knowledge base, facilitate public participation and cooperation in forest planning. Moreover, the fuzzy logic also allows for incorporating an uncertainty into the evaluation of ecosystem services. According to Pasadolas-Tato et al. (2013), it is a very important element in the decision-making process. Also, the simplicity of the heuristic approach of allocating priority areas in case of conflicting objectives by MOLA (Eastman 2016) supports a participative approach and transparency for allocation of support measures. A participative approach is enhanced with the possibility to define weights for the objectives in MOLA. I case of complex evaluation of many objectives the process of weights definition can be powered by methods like analytic hierarchy process or analytic network process (Saaty 2013).

Fuzzy logic and creation of membership functions are crucial in the evaluation phase of the proposed workflow. Subjectivity of the fuzzy models is often discussed (Marchini et al. 2009). We created the membership function for evaluation of erosion control service utilizing one complex quantified criterion – amount of soil loss, and the expert knowledge of tolerable or compensated erosion. A different approach was used in case of avalanche control service. The 13 membership functions were created for 9 criteria and those criteria were aggregated by logical operator AND. Sometimes the evaluation can be a more complex process, because of involving numbers of criteria or stakeholder preferences. For the purpose of objectivization of fitting the membership function, the artificial neural networks can be utilized (Jamsandekar & Mudholkar 2013).

The allocation of SES for the model territory is considered as a partial output, because it does not include all ecosystem services. The hydrological service is one of the most important in the entire area and some forest stands are recognized as a source of reproduction material, and it was not the subject of evaluation. We put an accent to methodological aspect and in aim to refer versatility of proposed workflow were chosen just a few services from each of three core sections of ecosystem services (provisioning, regulation/maintenance, cultural) classified by CICES (Haines-Young & Potschin 2018), before evaluation complex spectrum of ecosystem services in entire area.

Provisioning ecosystem services were represented in the current study with a wood production. When comparing the difference between the wood production potential and effect of the forest, the different spatial unit used for evaluation of SP and SE resulted in the inconsistency of evaluation. SE was evaluated for forest stands and SP was evaluated for management group of forest types (MGFT), what is spatially more aggregated unit. We recommend using the same spatial unit when evaluating SP and SE of any ecosystem service. It is important for planning of supporting measures which are in the proposed workflow based on finding the biggest differences between potential and effect of the forest on providing of ecosystem service.

The evaluation of cultural services has been included in the workflow by the form of constraints for utilization some of the provisioning services in favor of the planning of nature conservation objective. Five levels of territorial protection defined in our legislation and program NATURA2000 were used for evaluation purposes. This quite rough approach of evaluation can be supplemented by more detail ones. Mainly recreation and tourism ecosystem services can be addressed by numerous methodological approaches. Review on methods appropriate for the Carpathian protected areas was presented by Považan & Kadlečík (2014). The here proposed workflow is appropriate to implement most of them.

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Importance of using accurate input data was documented in case of the evaluation of avalanche control SE. The credibility of the evaluation was decreased by database uncertainty resulting from overestimation of rowan in the classification of image data, at the expense of spruce proportion, which has bigger avalanche control effect. Certain level of database uncertainty is a natural phenomenon in the decision-making process. It is therefore important to verify the reliability of the input data and to take this uncertainty into account when making a decision.

Selection of the models used in the phase of quantification of ecosystem service was oriented to using empirical and semi-empirical models. Currently, the research is oriented towards the development of more complex numerical (process-based, physical) models, which have more general validity. A disadvantage of this group of the models is their high demands on input data and parameters. Our goal was to propose system applicable in practical planning and this is a reason why we have chosen models with lower demand on inputs, but appropriately validated in the conditions of mountain forests.

5. Conclusions

We proposed here an innovative four-phase workflow of the evaluation of forest ecosystem services and of the zoning of priority areas. The workflow integrates the knowledge system and analytical functionalities of GIS. The non-financial system utilizing fuzzy logic for the evaluation purposes proved to be appropriate to compare the priorities of individual ecosystem services. This evaluation method has become the basis for the application of special GIS techniques for the zoning of priority areas and allocation of support measures for cases complementary as well as conflicting objectives. Comparison of the case study results with the existing map of ecosystem services has proved that the proposed system feasibly maps the potential of ecosystem services and allocates the supporting measures for the needs of multi-objective forest planning. We consider the proposed workflow to be a useful means for precise zoning of priority areas mainly in mountain forests where the use of ecosystem services needs to be particularly sensitive. The presented case study has the ambition to highlight the advantages and disadvantages of the proposed workflow and used tools. However, the creation of a generally applicable system for the evaluation of priority areas in the framework of multi-objective forest planning requires interdisciplinary approaches involving different teams of experts on ecosystem services. The here proposed system can represent a valuable contribution to such an effort.

Acknowledgment

The study was supported by project VEGA 1/0217/17/8 and by the Slovak Research and Development Agency under the contracts No. APVV-16-0325, APVV-15-0265.

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