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Modelling forest growing stock from inventory data: A data mining approach

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ABSTRACT

Growing stock is an ecological indicator of forest ecosystem response to natural and anthropogenic impacts that may result from forest management measures or environmental impacts. Information on growing stock is thus essential to understand dynamics of forest stands, their productive capacity and to manage their use within limits of sustainability. Dynamic changes of forest growing stock, as well as predictions of their future development, are usually estimated from the data gathered by national forest inventories using some mechanistic modelling approach. The resulting models are informative, but include many parameters, some of which are difficult to set or estimate. Due to the demanding parameterisation of mechanistic models, it is hard to achieve stability of their output accuracy, which can lower their predictive power. This paper presents an alternative and complementary approach of constructing models with machine learning and data mining methods. We applied these methods to the Silva-SI database and used the resulting interpretable models in order to find explanations for structural changes in Slovenian forests over the period from year 1970 to 2010. In addition, we developed predictive models for growing sock in the decade from year 2010 to 2020. The structure of the models describing temporal dynamics of growing stock shows that trends of growing stock are increasing for the entire studied period, while accumulation of growing stock is much more intensive after 1990. Forests with a lower growing stock are located either in the areas with non-favorable site conditions for forest growth, or at lower altitudes, where they are more exposed to human exploitation due to their vicinity to more densely populated regions. Predictions of growing stock for the decade 2010–2020 suggest that Slovenian forests will continue to accumulate their growing stock (private owned forests to 327 m^3/ha and state owned forests to 343 m^3/ha in 2020). The presented data mining approach that was here applied to the growing stock can also be used for investigating other ecological indicators.

1. Introduction

European forest resources are changing noticeably. Forest area in Europe (including European part of the Russian Federation) has expanded by 17 million ha during the past 20 years and the growing stock has increased by 8.600 million m^3 in the same period (SOEF, 2011). Forest in Slovenia is no exception and followed this trend with an increase of forest area available for wood supply by 5% (from 1.114 million ha in 1990 to 1.175 million ha in 2010) and growing stock of forests available for wood supply by 52% (from 256.3 million m^3 in 1990 to 389.9 million m^3 in 2010) (SOEF, 2011).

Magnitude and direction of changes of forest resources depend on a complex interplay between biological processes, abiotic constraints, initial state of forest stands and different natural and anthropogenic disturbances from both, controlled management, and other uncontrolled human induced activities. An initial state of forest stands and an applied forest management practice might be the two most important factors explaining changes in the forest structure and composition over shorter periods (a few decades) of time, while the impact of natural and social factors is indirect, through the differing conditions for forest management (Poljanec, 2008; Klopčič and Bončina, 2011).

Progress toward sustainable forest management can be assessed through the use of indicators as measures that provide information about potential or realized effects of human activities on forests. They are widely used on the national and international level such as in the Montreal Process of developing criteria and indicators for the conservation and sustainable management of temperate and boreal forests (Montreal Process, 2013) and in the Pan-European process of developing indicators for sustainable forest management in Europe and Russian Federation (State of Europe's Forests, 2011). In the suite of ecological indicators describing structural, compositional and functional characteristic of forests, growing stock plays

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a central role. Growing stock is one of the basic statistics of any forest inventory (Tomppo et al., 2010) and as such an indicator useful for various purposes. It is a fundamental element in determining the productive capacity of the area identified as forest available for wood production. Knowledge of a growing stock of the various tree species and its spatio-temporal dynamics is central to considerations of a sustainable supply of wood for products and the sustainability of the overall ecosystems. Growing stock can, by applying biomass expansion factors, be converted into estimates of above and below-ground woody biomass (e.g., Brown et al., 1999). Data on growing stock, increment and fellings are crucial for the calculation of carbon budgets in the forest sector (e.g., Karjalainen et al., 2003). Furthermore growing stock is also an important and well-accepted proxy for biodiversity.

It refers the properties that operate at a system level, including the appropriate species composition and the suitable environmental conditions that support processes of forest growth and development in particular and ecological integrity in general. Therefore growing stock can be attributed as an ecological indicator at system level which makes it particularly useful for forest management purposes. It is an indicator of forest ecosystem response to natural and anthropogenic impacts that may result from forest management measures or environmental impacts because it aggregates other state and stress indicators of forest ecosystem (i.e., quality of the soil, rainfall, temperature, growing stock increment, annual cut). Because of its systemic and integrative features, a growing stock can be used to assess the conditions of the forest, to diagnose the cause of structural or functional changes and to be used to predict future changes or trends of growing stock.

If the growing stock should be used for forest management on objective way, it has to diminish the three main methodological problems of use of indicators as a resource management tools (Dale and Beyeler, 2001): (i) too small number of indicators which are used to deal with complex ecological systems; (ii) problem of the selection of indicators which will enable understanding of the short-term, and long-term consequences of resource management decisions and (iii) difficulty with the interpretation of information provided with those indicators.

The dynamic changes of forest growing stock, as well as the predictions of their future development, at both European and national levels, are usually estimated from the data gathered by national forest inventories (Brassel and Brändli, 1999; Küchli et al., 1999; Risser, 2000) or, more rarely, by archival forestry data (e.g., Linder and Östlund, 1998; Axelsson et al., 2002; Ficko et al., 2011; Klopčič and Bončina, 2011). The European Forest Sector Outlook Study II (EFSOS, 2011) makes projections of European forest resources for a period from 2010 to 2030 and gives predictions of dynamic changes of forest resources at European and national levels. If no major policies or strategies are changed ("business-as-usual" scenario) in the European forest sector, the total forest area will increase by 6% (to 216.9 million ha in 2030) and the growing stock in the forest area available for wood supply will increase by 12% (from 174 m^3/ha in 2010 to 195 m^3/ha in 2030). The European Forest Sector Outlook (EFSOS, 2011) predictions for Slovenia show that the forest area available for wood supply will increase by 3% (from 1.175 million ha in 2010 to 1.211 million ha in 2030) and growing stock by 6% (from 334 m^3/ha in 2010 to 353 m^3/ha in 2030).

Predictions of the European Forest Sector Outlook Study II (EFSOS, 2011) are based on the results of several different modelling approaches. In particular, they respect outputs from econometric projections for production and consumption of forest products (Postma and Liebl, 2005; Arets et al., 2011), analysis of wood resource balance (Mantau et al., 2010), the results of the European Forest Information Scenario Model (EFISCEN) (Pussinen et al., 2001), and results of the European Forest Institute-Global Forest Sector Model (EFI-GTM) (Kallio et al., 2004, 2006). However, the majority of European countries have also developed their own tools for predicting dynamic forest changes at their national levels (e.g., Nabuurs et al., 1998). Common approaches to estimating and predicting future development of forest resources employ various methods, ranging from static inventory projections, to complex techniques of modelling. Such induced models usually project future forest development by using national forest inventory and yield data under some strong assumptions, like that the uncertainty of future growth is small and insignificant, or that the forest management doesn't change in time (Mohren, 2003). In some countries, detailed inventory and yield data are not available for sufficiently long periods of time (i.e., a few decades), and therefore, such models cannot be constructed.

Due to the large changes of forest stand structure (e.g., growing stock, forest area, tree species composition) noticed over the last few decades and changing climate and management objectives, improved spatio-temporal models for predicting changes of forest stand structure are required. These would not only provide a better insight into the complex interplay of growing and management conditions, but would also provide predictions of their future trends, which is necessary for improving forest policies, planning and decision making in order to ensure economically and ecologically sound forest management, and to reduce the risks due to the forecasted environmental changes. In addition, accurate predictions of future development of forest resources (e.g., growing stock, annual increment, etc.) are required for reporting carbon stocks and stock changes at national levels in accordance with the Kyoto protocol (Muukkonen and Heiskanen, 2005).

The most frequently used approach for predicting dynamic changes of forest resources is based on the modelling of forest variables among which the growing stock presents the most central one. This modelling task is usually based on mechanistic modeling approach, where the field data are used for calibration and validation of such models, while the models' structure is based on theoretical knowledge. Such an approach is informative, but includes many parameters, some of which are difficult to set or estimate. It often requires many different types of data that are not always possible to obtain (i.e., crown ratio, regeneration). Due to the large number of parameters that have to be fitted in mechanistic models, it is hard to achieve stability of output accuracy, which might also lower their predictive power (Jørgensen and Bendoricchio, 2001). In this context, dynamic changes of forest variables (e.g., the growing stock) are modeled using mechanistic modeling approaches that are based on: (i) patch (gap) models that operate at a different level of physiological detail of structural and compositional dynamics of forest ecosystem (simulation of forest succession, species distribution (e.g., PICUS (Jäger et al., 2004)), or under a wide range of environmental and management conditions (e.g., FORCLIM (Rasche et al., 2012)); (ii) individual-based models that explore various management and environmental effects on the ecological, structural and spatial dynamics of forest (e.g., MOSES (Hasenauer, 1994), CAPSIS (Dufour-Kowalski et al., 2012), iLand (Seidl et al., 2012)); and (iii) spatially explicit forest landscape models that simulate spatial projections of forest derived ecosystem services, and evaluate how these services will be impacted under future climate disturbance and management scenarios (e.g., LANDCLIM (Schumacher et al., 2004), LANDIS II (Scheller et al., 2007; Scheller and Mladenoff, 2007)).

In this paper we present a novel approach for predicting temporal dynamic changes of growing stock that can be regarded as an alternative or a complement to the above mentioned mechanistic approach. It is based on the application of machine learning and data mining methods to the forest inventory data. These methods can automatically generate (or learn or induce) models from