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Combining a growth-simulation model with acoustic-wood tomography as a decision-support tool for adaptive management and conservation of forest ecosystems

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ABSTRACT

The paper deals with the application of growth-simulation model SYBILA in conjunction with pulse tomography ARBOTOM for the evaluation of the strategy that was chosen for the management and protection of hardwood floodplain-forest in two study sites in Litovelske Pomoravi Protected Landscape Area (Czech Republic). The results of the simulation-growth model, supplemented by wood tomography showed that the current method of protection and management of the studied floodplain-forest ecosystems would lead to a change in habitat character, which is in conflict with the basic mission of Natura 2000. Simultaneous application of both non-invasive methods enables adjustments to the protected area management plan in accordance with the principles of adaptive ecosystem management. The results of the paper show that the combination of the two relatively new non-invasive methods of ecological research can be a promising support tool for adaptive ecosystem management and protection of forest ecosystems in protected areas.

1. Introduction

Floodplain-forests are among the key types of ecosystems of large rivers' floodplains of the European temperate zone (Klimo et al., 2008) and represent valuable refugia for biodiversity (Schnitzler, Hale, 2005). The increasing frequency of floods in large rivers floodplains in the context of climate change leads to the need for integrated floodplain management (Fliervoet et al., 2013). Therefore, floodplain-forest management is at the centre of environmentalists' attention, especially in seeking decision-support tools for conservation strategies applicable to Natura 2000 sites.

This article demonstrates the application of an innovative decision-support tool for sustainable management and protection of floodplain-forest ecosystems in the Czech Republic, which are protected under the European Natura 2000 network (Romportl et al., 2013). This decision-support tool is based on the application of a growth-simulation model in conjunction with wood-acoustic tomography. Growth-simulation models have been increasingly used as a support tool for the development of forest management plans in the last decade (Sedmak et al., 2013). Acoustic tomography has been applied in non-destructive analyses of the quality of wooden materials (Wang et al., 2009) and in arboriculture for non-invasive examinations of the mechanical stability of living trees (Schubert et al., 2009). The combination of a growth-simulation model and wood-acoustic tomography and its use for the evaluation of forest ecosystem management strategies is a totally innovative approach that has not been applied in European nature conservation so far.

Indent the present paper is to show that the combination of these two modern and non-invasive research methods could be considered as a promising support tool for the development of strategies for the protection and sustainable management of forest ecosystems in protected areas of international importance.

2. Materials and methods

2.1. Study sites

The research was conducted at two study sites Bahna and Vrapač situated in Litovelske Pomoravi Protected Landscape Area (PLA). The Bahna study site (33.34 ha) and Vrapač study site (80.69 ha) comprise the PLA core zone. Forest ecosystems at both study sites form a continuous complex of floodplain-forests classified as hardwood floodplain-forest of lowland rivers within the Natura 2000 classification (code 91F0). In spite of the differences in historical development of the study sites (see below), the character and species composition of the floodplain-forest vegetation at both study sites is very similar. The

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main stand level of the floodplain-forest ecosystem at both sites is formed by two dominant species (*Quercus robur* and *Fraxinus excelsior*).

2.2. History, forest management and conservation at the study sites

Both study sites differ in the history of anthropogenic impacts on the forest ecosystems. The floodplain-forest ecosystem at the Bahna study site originated from a coppice-with-standards forest. The lower storey was managed as a sprout forest until the 1950s. The upper storey was established by planting seedlings in the 1930s. The seedlings were grown from seeds of local origin from the area of today's PLA. The coppice forest management was terminated in the 1950s and since then the forest has been left to develop naturally as a forest reserve (for details see Machar et al., 2012). In contrast, the floodplain-forest ecosystem at the Vrapač study site had been managed, as a high forest with a deliberate preference for oak (*Q. robur*) as the main economic tree species since 1872. The current forest stands were established by planting seedlings in the 1930s (i.e. at about the same time as at the Bahna study site). The planting stock of oak trees was grown from acorns purchased from southern Europe (the Sava River catchment) and the planting stock of other tree species was of local origin (for details see Machar et al., 2009).

The study sites also differ in the level of anthropogenic impact on the river networks. The Morava River at the Bahna study site forms an anastomosing river system and the alluvial forest is flooded annually, usually in spring. At the Vrapač study site, the Morava River was regulated (straightened and enclosed in dykes) in the 1920s, as part of a flood protection project for the town of Litovel. Floods are very rare at the Vrapač study site and occur only during extreme flood events, e.g. in 1997 (Mácka 2009).

Sustainable forest management is currently applied consistently at both study sites, as so called non-intervention management, aimed at protecting biodiversity and the natural character of hardwood floodplain-forest habitat. This management complies with the requirements of Czech national legislation applicable to Natura 2000 priority habitat types and reflects a basic requirement for long-term maintenance of the habitat type and character (Miko, 2012).

2.3. Forest growth-simulation model and its verification by the method of acoustic-wood tomography

Predictions of the forest ecosystems' future development under the current non-intervention management were simulated for both study sites focused on the future development of the forest ecosystems' dominant trees. To create the model, tree-growth simulator SIBYLA was used, which consists of a set of mathematical algorithms in a comprehensive program package (Fabrika, Vaculciak, 2009). Dendrometric data on individual trees at the study sites (girth, height, horizontal and height position of the tree in the stand, trunk height, crown diameter, and the quality of the tree) were used as growth-simulation input data. This information was then displayed by the growth simulator in a specified future time period, as a 3-D model of a forest stand, for which biometric and ecological characteristics were generated (Pretzsch et al., 2002). Model visualizations and forest stand development simulations were performed for the time horizons of 20 and 40 years for both study sites.

To verify these growth models, a non-invasive analysis of the bole of selected individual trees was performed at both study sites using acoustic-wood tomography (Arciniegas et al., in press). The analysis was conducted with ARBOTOM impulse tomograph (Rinn, 1999), which is based on the finding that intact wood conducts sound faster than damaged wood with defects (Dackermann et al. 2014). The ARBOTOM measures the time it takes a mechanical pulse (a shock wave) to travel the distance between sensors placed on the tree trunk. The evaluation of the trunk measurements in two-dimensional tomograms then shows and quantifies cracks and cavities in the measured cross-section of the trunk (Yang, Luo, 2011). Sixty trees from the upper storey (30 oak and 30 ash) were analysed by the ARBOTOM device at each study site. Measured data from the tomograms at the two study sites were compared and statistically evaluated by a two-sample *t*-test involving two independent samples. To determine a potential relationship between the age of the tree (expressed as a trunk girth measured at a height of 130 cm above the ground) and the level of internal damage to the tree (expressed as a percentage of cracks from mechanical damage to the trunk according to the tomogram), Spearman's rank correlation coefficient was used and statistical significance was validated by a test criterion *t* using STATISTICA 6.0 CZ package (Zvára, 2003).

3. Results

3.1. Results of growth-simulation models

Growth-simulation models showed different predictions of the forest stand's future development for each of the study sites. The model of the forest ecosystem at the Bahna study site (Simon et al., 2014) showed that no significant changes in the structure and diversity of the tree composition are expected within a 20-year time horizon. However, some changes in the structure of the ecosystem will occur within 40-year time horizon, because the character of the forest stand will gradually change from the former coppice to high forest. The gradual spontaneous increase in the internal differentiation of the stand structure will lead to the reduction of stand density and the initiation of the expansion of free unstocked areas. Tree species composition will be similar to the current state.

In contrast, the model of the forest ecosystem at the Vrapač study site (Simon, Machar, 2014) showed that at this locality the non-intervention management will lead to the homogenization of tree composition, which will manifest itself clearly, especially in the 40-year time horizon. According to the model, the oldest oak trees (*Q. robur*) will gradually disappear. Ash trees (*F. excelsior*) will dominate the upper storey of the forest ecosystem and lime (*Tilia cordata*) will prevail in the lower storey of the forest stand. The structure of the tree component of the ecosystem will be similar to the floodplain-forests in the Morava River floodplain outside Litovelske Pomoravi PLA, managed under systems involving coupes (Maděra, Řepka, 2010).

3.2. Results

The results of non-invasive analysis of the boles of selected oak and ash trees by wood-acoustic tomography support the interpretation of growth-simulation models at both study sites. At the Bahna study site, the tomograms of boles of the studied trees showed a low level of internal mechanical damage (up to 19.6% for oaks and up to 17.4% for ash trees), at the Vrapač study site. However, the tomograms showed a markedly higher level of internal mechanical damage to the boles, especially for oak trees (up to 76.9% for oaks and up to 22.4% for ash trees). The results from the two study sites are significantly different ($t = 2.071$; $P = 2.014$). The better health of the dominant trees at the Bahna site study may explain the predicted state of the forest in 40-year time horizon (only a change in the stand structure without any significant changes in the species composition was predicted). No statistically significant relationship was found between the age of the trees and the degree of internal damage to the boles for either of the two analysed tree species (oak and ash) at the Bahna study site.

In contrast, a statistically highly significant correlation between the age of measured oak trees and the degree of internal trunk damage was found at the Vrapač study site (calculated value of the Spearman correlation coefficient $r = 0.79$). The test criterion $t = 3.21$ at significance level $\alpha = 0.05$ exceeds the critical value and, thus, confirms the existence of a real relationship (the older the oaks, the greater the degree of internal trunk base damage). No significant relationship was found between the age of ash trees and the degree of internal damage to their trunks at Vrapač study site. These results of wood-acoustic