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OPTIMAL CONVERSION MANAGEMENT FOR SPRUCE-DOMINATED FORESTS: THE CASE OF DRAHANSKA HIGHLANDS

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Abstract

With climate change, restoration of natural tree species in areas planted artificially with Norway spruce (*Picea abies* (L). *Karst.*) is among the main issues in Central European forest management. However, information on particular forest conversion strategies and on understanding their economic consequences are incomplete. To contribute, we develop a deterministic finite-time dynamic optimization model to understand the driving forces in the economically optimal conversion of spruce-dominated forests planted outside of natural conditions in South Moravia, Czech Republic. In addition to the commonly researched European beech (*Fagus sylvatica* (L.)), we also consider oak (*Quercus* (sp.)), Scots pine (*Pinus sylvestris* (L.) *Karst.*), and larch (*Larix decidua*) as alternatives to spruce and evaluate them from an economic point of view. The model recommends a steady reduction of the spruce fraction, replacing it preferably with oak, beech, and larch. The model validation shows that such a forest plan appears both ecologically advisable and economically optimal.

Keywords: cost function, dynamic optimization, forest management, forest conversion, mixed forests, reforestation strategy, revenue function, spruce

INTRODUCTION

Norway spruce (*Picea abies* (L.), further referred to as spruce) is well suited to humid continental climates but vulnerable to natural hazards and changing environmental conditions (Yousefpour and Hanewinkel, 2014; Knoke, 2008). As a fast-growing softwood species, spruce was extensively planted throughout Central Europe during the 20th century (Spiecker, 2003). For example, 34% of the Czech Republic area is covered by forests, and Norway spruce has dominated the Czech forest structure in the past hundred years (MACR, 2020), although outside of its natural conditions. In the natural tree composition, spruce did not exceed an 11% share, but today its share is about 50%, and spruce monocultures cover 23% of the total Czech forest land area.

For Central Europe it is expected that the frequency of extreme weather events and resulting forest disturbances such as drought, wind-throws and forest fires will increase considerably (Jandl *et al.*, 2015; Paul *et al.*, 2019; Dragievic, Lobianco and Leblois, 2016). This may particularly affect economically important spruce, which is highly susceptible to hazards such as drought, bark beetle outbreaks, and wind storms compared to broad-leaved species (Hanewinkel, Hummel and Albrecht, 2011; Knoke, 2008). Therefore, the conversion of spruce-dominated forests toward less susceptible broad-leaved species has been repeatedly emphasized (Pretzsch and Schuetze, 2009; Knoke, Gosling and Paul, 2020; Knoke, Messerer and Paul, 2017). An overall consensus has been reached that maintaining spruce monocultures in areas naturally habited by mixed and deciduous stands is unfeasible from the perspectives of both sustainable forest management and biodiversity preservation (Soucek and Tesar, 2008; Spiecker, 2003).

In view of the expected climate change and associated shift in vegetation levels, there has been a conversion of forest composition in the Czech Republic over the past two decades. However, this conversion has been very slow, and the spruce share decreased by less than 5% in total during this period. This shortcoming may be explained by the fact that forest composition conversion (FCC) into more natural mixed stands is a long-term process, changes in the representation of species are gradual, and the results will be reflected over several generations. Efforts to significantly reduce monocultures have thus far been hampered by the high initial cost of species composition modification in combination with the longevity of the task (Soucek and Tesar, 2008). Moreover, forestry professionals in Central Europe have been reluctant to change routines and their forest management practices has been characterized by inertia (Brunette, Hanewinkel and Yousefpour, 2020). Improving information on the conversion ecological and economical background could remove obstacles for conversion process in forest management. However, silviculture guidelines that allow the establishment and maintenance of forest mixtures under different environmental conditions remain unspecified, and the complex economic impact of spruce forest conversion is unknown (Coll *et al.*, 2018). Although research on mixed forest management has increased substantially in recent years, the new knowledge covers practitioners' concerns only partially (Coll *et al.*, 2018; del Rio *et al.*, 2016; Forrester and Pretzsch, 2015).

Most of optimization decision support tools developed regarding forest management so far solve the problems concerning tree rotation, harvest scheduling, and supply chain management, while FCC problems have rarely been tackled (Caglayan *et al.*, 2018). Moreover, dynamic optimization techniques that are appropriate for FCC problem solving are not widespread in forest management problems (Caglayan *et al.*, 2018; Ferreira *et al.*, 2016).

Owing to climate change, introducing an optimal structure and alternative species in FCC has arisen in the literature recently. Portfolio theory and the Markowitz model have been employed to reflect the consequences of tree diversification to support FCC knowledge (Dragievic, Lobianco and Leblois, 2016; Knoke, Messerer and Paul, 2017; Paul *et al.*, 2019; Neuner *et al.*, 2015). In Cerda and Martin-Barroso (2013), dynamic optimization based on an optimal control model was developed to determine the optimal land use. Janova and Hampel (2016) tackled the problem of insufficient data and suggested a simulation-based optimal control model for spruce stand conversion, and Manso *et al.* (2014) presented a stochastic multistage regeneration model for managing woodlands.

Thus far, European beech (*Fagus sylvatica* (L.)) has mainly been considered as the chief spruce alternative in FCC-related studies (see, e.g., Paul *et al.*, 2019; Knoke *et al.*, 2008; Pretzsch and Schuetze, 2009). Nevertheless, it is desirable to consider multiple species to support pending FCC decisions in central European forests. However, in-depth knowledge of species alternatives, needed for thorough FCC analysis, is limited and multiple-species conversion models are missing for the Central Europe.

Spruce monocultures have always been generally believed to be economically superior, outperforming other species in the Czech Republic (Stachova, 2018). Therefore, identifying whether it is economically advisable to convert spruce monocultures planted outside of natural conditions into more natural tree species has been a crucial question for the Czech Republic. The aim of this study is to answer this question, find the optimal conversion and provide understanding of its economic consequences. Particularly we (i) develop multiple-alternative-species dynamic optimization model for spruce-dominated forests out of their natural condition, (ii) find its solution and present an economically optimal long-run conversion of spruce monocultures to mixed stands in the Drahanska highlands, Czech Republic and (iii) support the model trustworthiness and applicability in forest management by comparing it with other FCC relevant models and with the results from real sustainable forest management in the area.

MATERIALS AND METHODS

Forest Composition Conversion Problem

The problem is to find the economically optimal long-run conversion of Norway spruce monocultures, which are out of their natural conditions in Central Europe, to mixed forest stands. A multiple-alternative-species dynamic optimization model with pure economic criteria will identify the optimal time path for forest composition and solve the FCC problem. Owing to gaps in in-depth knowledge of the ecology and economics of the alternative species, we create a generalised model that allows to build upon the given knowledge, advancing it using expert judgement and data simulations (Grimm *et al.*, 2020; Janova and Hampel, 2016). We develop a model for a representative forest management unit with simplified, locally typical natural conditions, forest management, and composition.

The FCC problem in the Drahanska highlands, located in the South Moravian Region of the Czech Republic will be addressed. The Drahanska highlands are a vaulted area with a mean altitude of 452 m above sea level with a rugged hilly character and 83,000 ha of forest land. Historically, the Drahanska highlands were predominantly populated by beech, oak, and their mixtures; the original forest structure was 77% European beech, and 16% oak with only a negligible ratio of Norway spruce. The current structure, however, is dominated by Norway spruce (*Picea abies* (L). Karst.) (45.6%), followed by European beech (*Fagus sylvatica* L.) (15%), Scots pine (Pinus sylvestris L.) (12.3%), oak (*Quercus* sp.) (8.3%), and larch (*Larix decidua*) (8%). Other species contribute towards lower ratios.

The dynamic conversion FCC problem was formulated in a simplified form as a general continuous optimal control problem in Janova and Hampel (2016). The main contribution was in the simulation design that enabled the delivery of missing underlying economic data when considering the risks of planting Norway spruce under natural conditions. In this study, we use the simulations established in Janova and Hampel (2016) as an input to obtain the actual underlying economic data, including the scenario considering the recent bark beetle attacks in Central Europe. We develop finite-time dynamic optimization model enabling a decrease in areas of all species and considering ecological constraints. We provide the complete dynamic time paths for each species that lead from the current to converted forest composition after 100 years.

We consider a forest composed of n tree species organized in large blocks[1], each showing the ecological characteristics of a pure forest. The ecological inter-species dependence, which occurs only within bordering zones, is negligible (Knoke and Seifert, 2008). Mixing large blocks with different tree species at the forest level will form a mixed forest. Although this lacks the ecological advantages of true forests mixed at the stand level, it reduces risk for the forest enterprise (Griess and Knoke, 2013).

The considered tree species are ecologically appropriate for any part of the considered area. Further, we consider real-world altitudinal zone distribution in the Drahanska highlands area. According to FMI (2000), the altitudinal zones distribution is: oak (1%), beech-oak (15%), oak-beech (44%), beech (28%), fir-beech (10%), and spruce-beech (2%). This suggests that beech is the dominant tree species from the ecological viewpoint and is only to be complemented by other species. Therefore, we assume that in newly planted forest stands other considered species will always be planted simultaneously/in combination with beech. Optimal rotation is known and provided for each species and the harvests take place annually, but for each stand only at the rotation age. The species distribution (total areas planted with the individual species) in the forest structure is allowed to change over time. After the tree harvest, the same or different species is to be planted. By the latter, the species distribution will be changed.

The aim of the model is to find an optimal path from current species distribution to species distribution after T years, which will maximize the total present value of future profits.

Model Formulation

To find not only the optimal species distribution in the forest but also the time path leading to this terminal state, we use dynamic optimization as an appropriate modelling approach.

The optimal control formulation of a dynamic optimization problem focuses on control variables u that serve as an instrument of optimization and are subject to the decision maker's choice. In the forest conversion problem, the role of control variables is played by the speed of change of areas covered by individual species. Once the optimal control path is found, the optimal state path x, representing the species distribution, may be found subsequently. Although theoretically known, solution processes for optimal control problems are not trivial.

We consider a representative artificial forest management unit (AFMU) in the Drahanska highlands with an area of A = 216 ha. The AFMU possesses simplified the Drahanska highlands, locally typical natural conditions, forest composition, and forest management practices.

For optimization, four typical species were considered as alternatives to spruce. We denote $n = 5$ as the total number of species in the AFMU forest. We denote the individual species by index i: i = 1 – Beech, 2 – Oak, 3 – Pine, 4 – Larch, and 5 – Spruce. As the decision will be taken annually, we formulated a discretized finite-time optimal control problem. The state variables represent the species distribution in the forest, and x_{it} is the total area forested by species i in year t. The AFMU initial state x_0 = (36.4, 20.1, 29.8, 19.4, 110.6) ha represents the current the Drahanska highland species distribution. The control variables u_{it} represent the change in the total area forested by species i between years t and t - 1. The objective is to maximise the present discounted value of profit from the forest stand within T = 100 years and find the optimal dynamic path from the current to the terminal species distribution.

The objective function is formulated according to Samuelson's recommendations for finite-time horizon dynamic decision problems (Samuelson, 1976):

$$V = \sum_{t=1}^{T} \delta^t \Pi_t + \delta^T V_T, \tag{1}$$

where $\delta = (1 + r)^{-1}$ is a discount function with $r = 0.03$ being a given interest rate, Π_t is the annual profit, and V_T is the terminal value function.

The annual profit Π_t is calculated as the difference between annual revenues from timber sales G_T plus subsidies σ_t for changing the forest structure to ameliorative species and annual costs of forest management activities F_t:

$$\Pi_t = G_t + \sigma_t - F_t. \tag{2a}$$

1 The term “large blocks” is used to differentiate the mixtures on the forest level — mixtures in *large blocks* — from the mixtures at the stand level — in *small blocks*, see, e.g., (Knoke *et al.*, 2008; Paul *et al.*, 2019).

Following the assumptions made in Caparros *et al.* (2010), we adopt the quadratic functional forms. In forest management decision support, the prevailing technique is linear programming, while quadratic programming is used rarely (for FCC related problems see (Arias-Rodil, Dieguez-Aranda and Vazquez-Mendez, 2017; Pyy *et al.*, 2017)). The rationale for using the quadratic functions in the objective of the FCC model stems from the good performance of the empirical regression model combined with the correspondence of the resulting functions with expert suggestions concerning revenues and costs in the particular FCC problem (Janova and Hampel, 2016; Hampel and Viskotova, 2020). The revenue and cost functions are considered in the following forms:

$$G_t = \sum_{i=1}^{n} (g_{i0} + g_{i1} x_{it} + \frac{1}{2} g_{i2} x_{it}^2) \quad (3)$$

$$\sigma_t = \sum_{i=1}^{n} \sigma_i u_{it}, \quad (4)$$

$$F_t = \sum_{i=1}^{n} (k_i + a_i x_{it} + b_{i1} u_{it} + \frac{1}{2} b_{i2} u_{it}^2), \quad (5)$$

where g_{i0}, g_{i1}, g_{i2}, k_i, a_i, b_{i1}, b_{i2} are constant parameters to be estimated for particular conditions of the Drahanska highlands, and σ_i are the given subsidies per ha of newly planted ameliorative and soil improving species.

The terminal value function V_T represents the total value of the established forest. We assume that forest conversion will be accomplished during the planning period, and no further changes in land use are considered beyond T, that is, $u_{it} = 0$, $1 \le i \le n$, for $t \ge T$. Therefore, from (2a), (3–5), we obtain

$$\Pi_T = \sum_{i=1}^{n} (g_{i0} - k_i + (g_{i1} - a_i) x_{iT} + \frac{1}{2} g_{i2} x_{iT}^2), \quad (2b)$$

and we approximate the terminal value function by summing the net present values of the annual future profits Π_T as

$$V_T = \sum_{\tau=1}^{\infty} \delta^{\tau} \Pi_T = \frac{\delta}{1-\delta} \Pi_T. \quad (2c)$$

The dynamic optimization problem formulation with objective (1) takes the form:

$$\max V = \sum_{t=1}^{T} \delta^t \Pi_t + \frac{\delta^{T+1}}{1-\delta} \Pi_T \quad (6)$$

subject to

$$x_{it} = x_{i(t-1)} + u_{it}, \quad (7)$$

$$\sum_{i=1}^{n} x_{it} = A, \quad (8)$$

$$u_{2t} + u_{3t} + u_{4t} \le u_{1t}, \quad (9)$$

$$-x_{i0}/\rho_i \le u_{it},\ \rho_i = const_i, \quad (10)$$

$$0 \le x_{it}, \quad (11)$$

$$0 \ge u_{5t}, \quad (12)$$

$$x_0 \text{ given}, \quad (13)$$

$\forall t \in \{1, \ldots, T\}$, $i = 1, \ldots, n$.

The dynamics of our problem is formulated through constraint (7), while constraint (8) ensures that the total area of the forest is constant A throughout the planning period. Constraint (9) stems from the assumption of real distribution of altitudinal zones in the Drahanska highlands. The general constraint interconnects the total change of areas of oak, larch, and pine with that of beech. The choice of the parameters in (9) is based on the assumption that beech is the dominant tree species from the ecological viewpoint and is only to be complemented by other species. Constraint (10) restricts the annual decrease of the area of species i to the area of this species in its rotation age ρ_i. There are nonnegativity conditions (11) for all the state variables. Constraint (12) represents the requirement of nonpositive changes in the spruce area, i.e. either the spruce area remains the same or can be decreased. Finally, (13) represents the given initial state, i.e. the initial area distribution in the Drahanska highlands.

Estimation of the Revenue and Cost Functions

To develop the computerized model, we need explicit expressions for annual revenue and cost functions. However, only limited data sources are available for the forestry industry, as companies do not present their costs and revenues in a sufficiently detailed structure. Hence, there is not enough data for the Drahanska highlands to directly estimate the annual revenue and cost functions (3) and (5). Therefore, we used the simulations suggested and described in (Janova and Hampel, 2016; Hampel and Viskotova, 2020) to obtain the data for the regression analysis.

Particularly, we estimated two data sets: (A) for "common" years, which consider only the long-term stable prices in the pre-bark beetle period 2011–2013, and (B) for "bark beetle" years, which are based on the prices in 2017–2019 (in the following, we refer to these as the *normal scenario* and *bark beetle scenario*, respectively). These revenue and cost functions incorporate the uncertainty of yield and prices as well as variability stemming from area specifics and represent the annual mean of long-run revenues and costs for each species in the forest area.

We collected real data on the structure of forests, forest land characteristics, and technological and economic characteristics of forest cultivation, felling, and timber sales. The data were acquired from state agencies (Czech Statistical Office, Forest Management Institute, Ministry of the Environment) and from the Mendel University Training Forest Enterprise Masaryk Forest Křtiny, which manages 10,000 ha of forest land in the Drahanska highlands, and is engaged in forest cultivation, and sale and processing of timber.

Employing the normal and bark beetle simulation datasets, we estimated the parameters of annual revenue (3) and cost functions (5) for the two scenarios; the ordinary least squares method was used for this purpose. The revenue and cost function parameters are presented together with the current unit subsidies σ_i in Tabs. I, II. The estimated parameters are statistically significant at the $\alpha = 0.05$ level with high coefficients of determination (above 0.98, for each function) and consequently with high quality of regression.

RESULTS

The optimal control model (6–13) has the form of a quadratic programming model (QPM) with $2nT$ decision variables x_{it}, u_{it}, $1 \le i \le n$, $1 \le t \le T$, linear equality constraints (7–8), linear inequality constraints (9–10) and upper and lower bounds (11–12). The given initial point x_0, see (13), together with linear constraints (7), fully determine the dynamics of our system. Note that in the case of a 100-years planning period, we arrive at a QPM with 1,000 variables. We used MATLAB Quadprog solver to obtain the solution for the two scenarios:

- **Scenario A:** No bark beetle calamity effects considered, normal scenario parameters applied throughout the whole planning period and
- **Scenario B:** During the initial part of the planning period, the revenue and cost functions will be affected by the bark beetle calamity in Central Europe and bark beetle scenario parameters apply. Then, we assume that the recovery and normal scenario parameters will apply for the rest of the planning period.

Scenario B reflects the recent 2016–2020 bark beetle experience in Central European forests. In our model, we deal with forests not badly damaged by bark beetles, that is, the volume of annual salvage felling does not considerably exceed the volume of timber planned for harvesting in a particular year. However, forest profitability is affected by price drops in the timber market during the bark beetle period. We consider the initial part of scenario B to be 10 years, where bark beetle effects occur. This was set according to historical experience in timber price dynamics, where recovery took approximately twice the duration of the disturbance period.

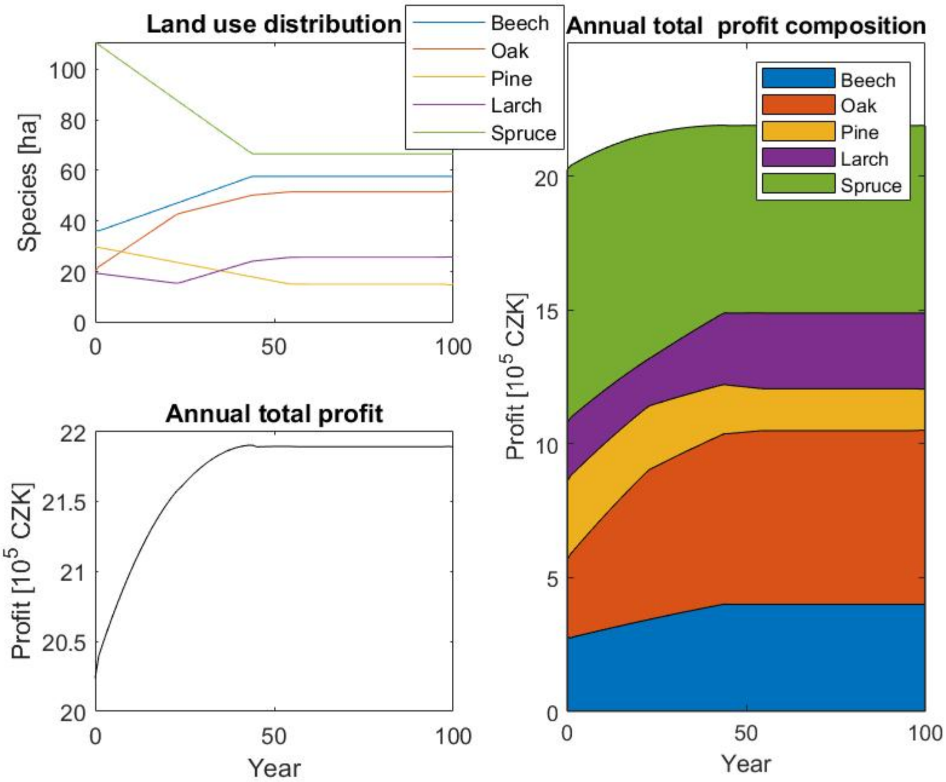
The results for scenarios A and B are shown in Fig. 1 and Fig. 2: We can see the time paths for total areas covered by the individual species, the time evolution of the total annual profit, and its decomposition among contributions from individual species. The chosen terminal horizon T provides sufficient time for the model to arrive at a stable solution without the need to change the species distribution further. Since total annual profit increases during the forest conversion period, the expected total annual profit after forest conversion is higher than that from current, spruce-dominated forests. This result is highly important for forest management, as the trust in the economic superiority of spruce was the driving force that balanced forests in Central Europe towards spruce monocultures for centuries.

I: *Coefficients of annual cost and revenue functions (3–5): normal scenario; in 10^4 CZK per ha*

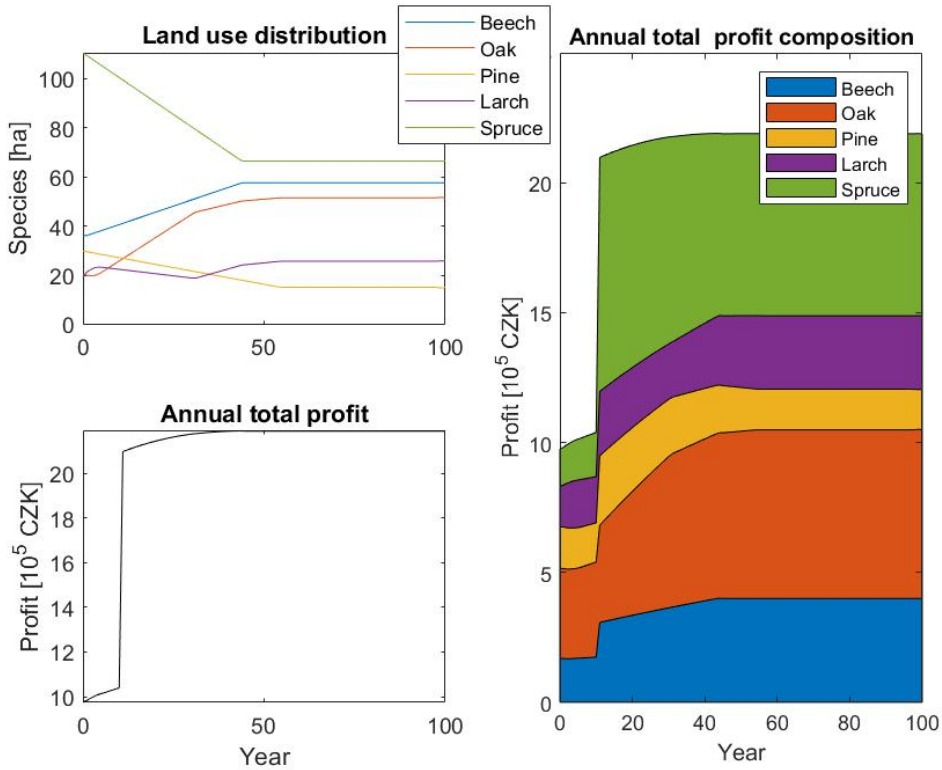
i	Species	g_{i0}	g_{i1}	g_{i2}	k_i	a_i	b_{i1}	b_{i2}	σ_i
1	Beech	0.008	1.116	-0.006	0.044	0.241	-0.020	0.002	0.163
2	Oak	0.019	1.723	-0.011	0.046	0.183	-0.035	0.003	0.150
3	Pine	0.018	1.345	-0.007	0.047	0.25	-0.022	0.002	0
4	Larch	0.015	1.479	-0.009	0.050	0.258	-0.028	0.002	0
5	Spruce	0.013	1.623	-0.009	-0.057	0.271	0	0	0

II: *Coefficients of annual cost and revenue functions (3–5): bark beetle scenario; in 10^4 CZK per ha*

i	Species	g_{i0}	g_{i1}	g_{i2}	k_i	a_i	b_{i1}	b_{i2}	σ_i
1	Beech	10.948	0.768	-0.003	2.434	0.477	0.473	-0.013	0.163
2	Oak	19.822	1.117	-0.005	-4.933	0.571	0.377	0.517	0.150
3	Pine	4.996	0.990	-0.005	1.312	0.507	0.353	0.096	0
4	Larch	1.615	1.429	-0.008	0.890	0.578	0.396	0.054	0
5	Spruce	2.139	1.291	-0.007	-2.431	0.808	0	0	0



1: *Optimal conversion time path in Scenario A: No bark beetle calamity effects considered*



2: *Optimal conversion time path in Scenario B: First ten years in the planning period affected by the price drop caused by the bark beetle calamity*

During the initial planning period, the profit graphs differ substantially between the two scenarios; in scenario B, there is a decrease in profits compared to scenario A. However, the time paths of total areas covered by particular species do not differ substantially, and in both scenarios, the model arrives at the same terminal area distribution. However, one must remember that the model is intended for use in forests not badly damaged by the bark beetle calamity. This means that forest management is affected only by the price drop and not by the loss of a considerable volume of timber. Under such an assumption, **the long-term steady state expressed by the optimal forest composition is the same, despite the initial price disturbance by the bark beetle effects**.

The time paths in both scenarios show the forest structure conversion up to a certain steady state. The areas of spruce and pine are decreasing, and the ratios of beech and oak are increasing. This behaviour is robust and corresponds to the expert suggestion: both broadleaf species are natural in the area, are reasonably and highly profitable, and are expected to improve forest resistance to drought and climate change. The model suggest that spruce and pine should be replaced by beech and oak and possibly also by larch, but the particular species distribution must be accommodated to the particular natural conditions of the forest site. The speed of reduction of the spruce area is given by the rotation of spruce-only areas where spruce was harvested in its rotation age and is to be reforested by new species. It is important that the optimal time paths lead to a terminal state based only on economic objectives, and **the model establishes the ecological recommendations for substantial replacement of spruce from an economical point of view**.

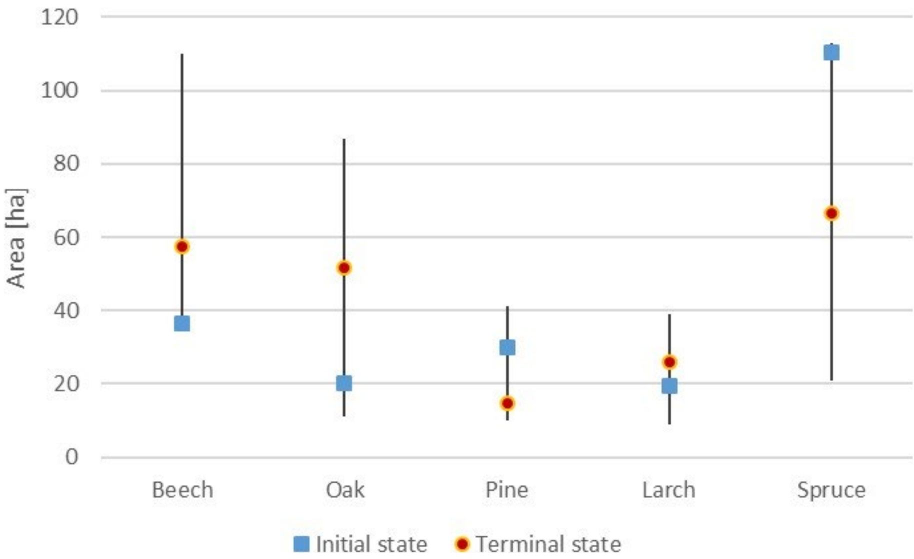
The optimization model is robust in respect of changes in subsidies, which play the role of a parameter in the objective function. Changing the subsidies in the model did not affect the solution considerably until the subsidies were 10 times their current level in the Czech Republic. This information is interesting from the policy-making perspective: subsidies at current levels will not play a key role in establishing the optimal forest plan.

DISCUSSION

To understand model accuracy and applicability for the forest manager, we discuss validity of the model and its results in light of recent FCC relevant models. In forestry research, significant attention has been devoted to understanding the ecological consequences of conversion from spruce monoculture to mixed forests at the species, stand, and forest levels (e.g. Juchheim *et al.*, 2020; Morin *et al.*, 2020; Sousa-Silva *et al.*, 2018; Liu, Kuchma and Krutovsky, 2018; Schwaiger *et al.*, 2018; Cordonnier *et al.*, 2018; Brave *et al.*, 2019; Hertzog *et al.*, 2019 from the most recent). Stemming from research on forest conversion ecology, systematic management of forest management and economics of mixed forests has emerged recently (Knoke *et al.*, 2005; Knoke, 2008; Paul *et al.*, 2019 and Friedrich *et al.*, 2019). An increasing number of studies provide evidence that mixed-species stands can overyield monocultures, but it is still not fully understood how overyielding at the stand level emerges from the tree, canopy, and size structure (Pretzsch and Schuetze, 2016; Knoke *et al.*, 2020). From a risk-averse perspective, the economic value of a mixed-species forest is considered greater than that of a mono-species forest (Knoke *et al.*, 2008). In Wieldberg and Moehring (2019), it was shown that forest enterprises with a diversified tree composition will not yield the highest possible return but are able to minimise the risk for a given level of return. Considered paralelly, there are strong indications that mixed stands may have the same or even better productivity compared to pure stands. Mixed-species stands are better able to compensate biotic and abiotic disturbances and may, therefore, lead to a significant reduction in financial risk compared to monocultures.

Our optimization model is in compliance with the cited findings concerning the rising economic value of forest stands with increasing ratios of broadleaf and deciduous species. Note that the mentioned models provide more detailed views on ecology and production when considering mostly conversion to single species (typically beech), while our model delivers new (yet general) insights into the possible optimal conversion from spruce to multiple species forests.

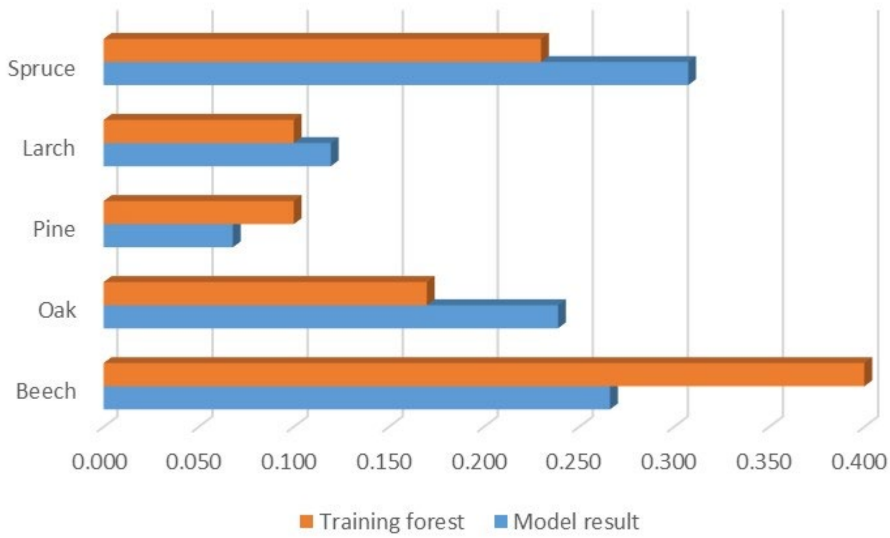
To evaluate the feasibility of the solution from the ecological point of view we used real expert information. The target species composition recommended for future forests originating from 2000–2020 management is stated in the official forest development plan for the Drahanska highlands (FMI, 2000). In principle, the plan advises to plant forests with a high spruce ratio (approximately 50%). However, a qualitative recommendation to plant spruce only in mixtures with mainly beech, oak, larch, and pine due to expected climate change and shrinking of higher altitude zones in the area appears in the plan. It was also advised to allow for the natural conversion of spruce-dominated forests to the original species. From the species composition suggested at different sites in the Drahanska highlands, we estimated the ecologically advisable area intervals for each species in our model problem (see vertical lines in Fig. 3). The optimization model suggests a terminal species composition of 27% beech, 24% oak, 7% pine, 12% larch, and 30% spruce for the 100-year planning period, which is within the ecological intervals for the individual species advised by experts in the Drahanska Forest Development Plan (see Fig. 3).



3: *Forest species composition of the Drahanska highlands: initial and terminal state of the optimization model. The vertical lines represent the interval of ecologically advised species composition for the Drahanska highlands concerning the site variety*

For further discussion we take advantage of the experience and information provided by the Training Forest Enterprise Masaryk Forest Křtiny (www.slpkrtiny.cz). The training forest covers area of more than 10,000 ha of the Drahanska highlands forming its southern part. It was established 100 years ago and since the beginning the aim was to apply sustainable forest management appropriate for the locality. This aim seems to be well fulfilled as the training forest has experienced very little damage from the recent bark beetle calamity compared to other forests in the area. Today, the forest stands of the training forest are typically mixed with beech, oak, pine, larch, and spruce, all together covering 82% of the whole forest area. Among these five species, currently there is 40% beech, 17% oak, 10% pine, 10% larch, and 23% spruce.

Comparing this with the results of our model (see Fig. 4) we can see that in the training forest there are higher ratios of beech and pine, while spruce, oak and larch are planted in lower ratios compared to the model. Concerning the fact that in the Drahanska highlands, climate change will considerably affect the natural conditions, the average temperature is expected to increase, and lower elevation zones will spread massively, managers of the training forest have specified a target for oak as high as 30% at the expense of spruce and partially also beech (with respect to the total area of the five species considered in our study). To sum up, the training



4: *Species distribution: Model result compared to the current state at the Training Forest Enterprise Masaryk forest Křtiny* forest plans correspond with the model results in main features: oak and beech being the principal species and spruce areas being decreased – although in different ratios. The considerably lower ratio of spruce in the training forest corresponds to the prevalence of lower altitudinal levels within the area of the training forest.

As the model is generalized and provides generalized economically optimal recommendations, the results must consider the particular natural conditions of the forest area. Therefore, a perfect match between a particular solution in the training forest and the generalized model is neither expected nor required. The good correspondence between real data from successful sustainable forest management and the theoretical concept supports the reliability of the model.

CONCLUSION

This paper aimed to provide a decision support for understanding the driving forces in the economically optimal conversion of spruce-dominated stands outside of their natural conditions to multi-species mixed forests in Central Europe. For this purpose, we developed a dynamic optimization model for the generalized conditions of the Drahanska highlands. The model provides positive answer to the question of the economic relevance of converting spruce dominated forests. Particularly, the conversion is not only desirable from the ecological viewpoint, but it is also economically advantageous.

The model provides a particular timeline of the species distribution. It is recommended that the spruce be steadily reduced in area, preferably replaced by oak and beech, and possibly also by larch, up to the terminal species composition of 27% beech, 24% oak, 7% pine, 12% larch, and 30% spruce. This result appeared to be ecologically feasible according to local specific ecological guidelines, but was also validated by comparison with the real sustainable forest management experience of the training forest, covering almost 15% of the Drahanska highlands forest land.

A very similar dynamic path of the species distribution and the same terminal state were obtained for the normal- and the bark beetle scenario. This indicates that in a long term, forests not severely damaged by bark beetles will not be seriously affected by a temporary drop in timber prices.

The model results may be used as a decision support to obtain insight into the driving forces of optimal spruce conversion. As it represents only an average forest in the Drahanska highlands, the results should be customized to a particular site. The results form a decision support for experienced forest managers, who are capable of deciding on the forest plan but lack knowledge of the economic consequences inherent to spruce-dominated forest conversion. Our model can be used alone or in combination with other models that focus on further ecological, production, and/or landscape issues of forest conversion so that forest managers may obtain integrated decision support.

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