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Using FORDRY model to forecast transformation of Norway spruce (*Picea abies* (L.) Karst.) stands in Nadsyansky Regional Landscape Park (Ukrainian Carpathians)

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Abstract

The aim of this study was to simulate transformation of species composition, biomass and number of treesin spruce stands depending on a possible combination of cutting and planting scenarios as well as climate changes. The FORDRY computer model was used to predict the dynamics of Norway spruce (*Piceaabies* (L.) Karst.) stands in Nadsyansky Regional Landscape Park in the Ukrainian Carpathians. Potential changes in species composition, biomass and number of trees were forecasted for the next 50 years. Four scenarios, first – warm-dry, second – cutting dead spruce trees, third – cutting all trees andfourth – planting, were compared to the control one. The analysis revealed a rapid decrease of stand biomass in the first decade as a result of spruce decline. The model predicts an increase in beech biomass before the 50th year of simulation in all scenarios. In the planting scenario, the biomass of beech increased up to 199.9 ± 6.9 t·ha^{-1} in the 50th year. Correlation analysis showed weak autocorrelations of spruce and negative cross-correlations of spruce with the total stand in control and other scenarios. The output of performed simulations is supported with field and literature data. Results of this study can be applied in the long-term planning of the management and conservation activities in this region. The application of FORDRY model was found useful for analysing the potential scenarios of spruce stand transformation in Nadsyansky Regional Landscape Park.

Key words

spruce forest decline, tree biomass, tree number, species composition, prediction, simulation experiment, gap model

Introduction

Transformation of spruce stands is a current issue particularly in Central and Eastern Europe, especially in the Ukrainian Carpathians, where spruce forests are widely distributed and occupy large areas. During the last two centuries, their area increased from 126,000 to 325,000 ha (Golubets 1978). At the present time, a decline of spruce forests is visible on an area of 19.300 ha in the Ukrainian Carpathians (3% of spruce forests'

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area) with a wood volume of 5.8 million m^3. Spruce forest decline does not depend on forest type (Parpan et al. 2014; Shparyk 2014). Secondary spruce stands dominate in the Nadsyansky Regional Landscape Park (which is located in the Ukrainian part of the Trilateral East Carpathians Biosphere Reserve). They have turned out to be biologically unstable and require conversion (Stoiko 1999).

Recent studies have focused on transformation of spruce forests that leads to increased productivity and biomass (Pretzsch et al. 2010; Shparyk 2019; Bałazy 2020), reduced risk of windfalls (Schutz et al. 2006), better resistance to drying and reduced risks of the impact of pathogens (Parpan et al. 2014), improved soil conditions (Prescott 2002) and improved biodiversity (Shparyk 2019) of the transformed forests. Results of this activity clearly depend on the forest types and methods of transformation (Schutzet al. 2006; Parpan et al. 2014).

However, to elaborate on the optimal methods for the transformation of spruce forests, it is essential to develop simulation models that can be used to predict spruce forest development within different management and climatic scenarios. A recent complex model implemented in the SIBYLA growth simulator showed the need for evaluation on the scientific level for the analysis of changes in tree increment and tree quality of living trees due to damages (Fabrika and Vaculčiak 2009). The use of GADA model is of much perspective in the Czech Republic due to its precise prediction of future diameter growth which can be useful for estimating the volume growth, biomass and carbon amounts of Norway spruce forests (Sharma et al. 2017). The next model that was used for the analysis of conversion regime of spruce stands in Germany was tested by SILVA 2.1 simulator (Hanewinkel and Pretzsch 2000) and showed that the losses in standing volume due to premature cutting, in order to create regeneration gaps, are of great importance. The growth simulator SILVA 2.2 is also a suitable instrument for planning intermediate cuttings (Šmudla 2004). The Polish model FORLAS (Brzeziecki 1999) was created and parameterised based on field data from different forest regions in Poland. FORDRY model was created for the purpose of simulating stand drying. This model has special tools for forecasting spruce decline, autocorrelation, cross-correlation statistical analysis and 3D visualisations.

The aim of this study is to analyse and simulate transformation of species composition, biomass and number of trees of spruce stands depending on a possible future combination of cutting and planting scenarios and climate changes using the FORDRY model. The hypothesis is that in the next 50 years the spruce is not going to be the dominant species in Nadsyansky Regional Landscape Park in terms of tree number and biomass.

Material and methods

Study sites

This study was conducted on three permanent plots (Fig. 1). The area of each plot is 625 m^2. The plots are situated at an altitude of 690–692 m a.s.l. in the Nadsyansky Regional Landscape Park (49°11'27"N, 22°45'16"E). According to the data from the Turka meteorological station (594 m a.s.l.), the average air tem-

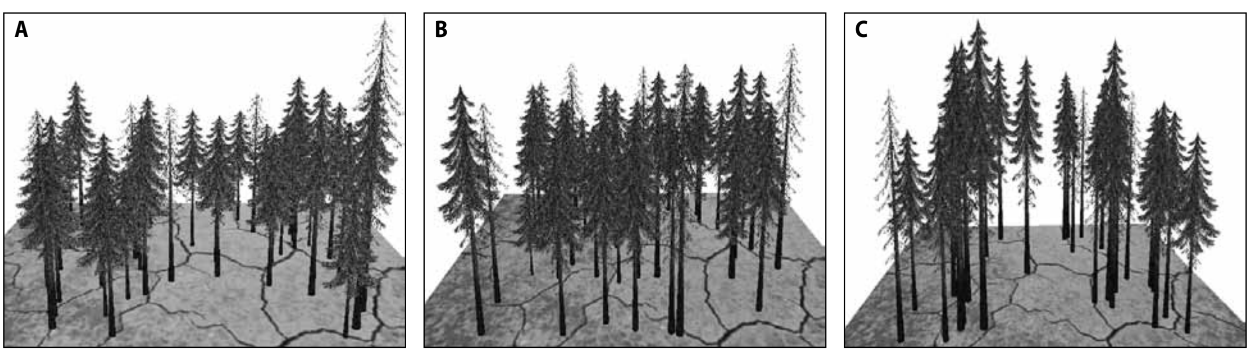

Figure 1. Three-dimensional visualisation of Norway spruce stands occurring on the sample plots at the beginning of simulation (A, B and C –plot nos. 1, 2 and 3, respectively)

peratures are –6.1°C in January and 16.0°C in July. The average annual temperature is 5.6°C and the average annual precipitation sum is 841 mm (Stoiko 1999).The light and shallow brown soil on the Carpathian flysch is characteristic for plots.

Species composition of the plot stands consists of spruce (*Picea abies* (L.) Karst.): 35 trees on plot 1, 34 on plot 2 and 25 trees on plot 3. Basic characteristics of spruce trees on the permanent plots are presented in Table 1.

Table 1. Basic characteristics of spruce trees occurring on study plots

Plot	$DBH_{1.3}$ [cm]			H [m]			Mean age [years]	n
	mean	min.	max.	mean	min.	max.		
1	20.3	8.0	32.0	19.2	5.5	24.5	43	35
2	22.4	10.5	33.5	19.4	6.5	24.0	46	34
3	25.9	13.5	36.5	21.8	7.0	25.0	51	25

The development of tree biomass and number was first analysed for control conditions (actual sum of effective temperatures amounting to 1475°C degree-days and average annual precipitation amounting to 841 mm). Next, simulations were conducted forfour scenarios: first – warm-dry, second – cutting dead spruce trees only, third – cutting all trees and fourth – planting.

In the control and in the first scenario, simulations were carried out without any management changes being made. Dead spruces were not removed, but were left to the natural decaying process. In the first scenario, simulations were conducted assuming an increase in the sum of effective temperatures and decrease in precipitation only. Taking into account the fact that the average temperature in Europe has increased by 0.95°C (IPCC2007) from 1906 to 2005, our estimation for the first (warm-dry) scenario assumed a further increase in temperature by 1.0°C per day during the vegetation period. This resulted in a total increase in the sum of effective temperatures for the permanent plot by 200°C degree-days. In the FORDRY model, we also assumed a reduction of precipitation during the vegetation period by 200 mm. In the second and third scenarios, additionally some cuttings were made in the first year of simulation time.

The fourth scenario means that the stand was cut down by clear cutting and after that artificially regenerated. Initial sapling density in regeneration was 6000 ind.·ha^{-1} of beech (*Fagus sylvatica* L.), fir and spruce, which means 375 trees in total (beech – 130, fir – 125, spruce – 120) per analysed permanent plot (25 m×25 m) without any further silvicultural treatments. Each plot was simulated 200 times in Monte Carlo statistical realisations, which corresponded to 200×0.0625 ha = 12.5 ha. Simulations in control and all other scenarios were carried out for a period of 50 years. The time step of the model is 1 year.

Hemispherical photographs (nine locations per permanent plot) were taken as required for verifying the leaf area index (LAI) calculations performed by the FORDRY model. Gap Light Analyser software (Frazer et al. 2000) was applied for hemispherical analyses. The age of the trees was analysed using a Pressler borer. The height of each tree was measured by a Blume Leissa altimeter. Illumination was measured using an LX-108 light meter. All data received have been entered into the FORDRY model. The output of the model was the predicted number and biomass of trees. The data from plots including $DBH_{1,3}$, height and crown projection of each living tree were used to initiate the model, parameter estimation and model calibration.

Description of fordry model

The FORDRY model belongs to the group of gap models (Botkin 1993) that simulate the long-term dynamics of forest ecosystems, taking into account the influence of the most important environmental factors, such as temperature, precipitation, light and soil nutrient content, on the main processes taking place in the stands: regeneration, growth and decline of individual trees. The model simulates reproductive processes (block BIRTH), growth (block GROWTH), mortality (block DEATH) and drying (block DRYING) of trees during every year, as well as the influence of additional environmental and ecological factors upon the tree stand.

Among the factors considered are the annual sum of precipitation (block PRECIP), annual sum of effective temperatures DGD (degree days) for vegetation (block TEMP), nitrogen contents in the soil (block NUTRIENT) and degree of shading of the area (block LIGHT) by tree crowns.In the FORDRY model, the process of tree growth is determined by the equation:

$$\delta\left(D^2H\right)= rLa\left(1-\frac{DH}{D_{\max}H_{\max}}\right) \quad (1)$$

where:

r – species constant, describing photosynthetic efficiency of assimilation apparatus,
La – relative tree leaf area in m^2/m^2,
D – tree diameter measured (in cm) 1.30 m above ground level,
H – tree height in cm,
D_{max} – species maximum diameter in cm,
H_{max} – species maximum height in cm and
$\delta(D^2H)$ – tree volume increase in cm^3.

The available light function describes the amount of light available for specific tree leaves and is calculated according to the equation:

$$Q(h) = Q_{\max}e^{-k \cdot LA(h)} \quad (2)$$

where:

$Q(h)$ – solar radiation at height h,
Q_{max} – solar radiation above the treetops,
k – constant value – 0.25,
e – exponent,
$LA(h)$ – total tree leaf area in the plot, above height h.

The coefficient of influence of thermal conditions on the growth rate is defined as:

$$t=\frac{4\left(DGD-DGD_{\min}\right)\left(DGD_{\max}-DGD\right)}{\left(DGD_{\max}-DGD_{\min}\right)^2} \quad (3)$$

where:

t – index of growth reduction,
DGD – sum of effective temperatures for an individual site,
DGD_{min} – minimal sum of effective temperatures needed for species occurrence and
DGD_{max} – maximum sum of effective temperatures for species occurrence.

The influence of external conditions is factored into the annual tree volume increase process. The actual increase in tree volume $\delta(D^2H)_{real}$ results from the optimal increase $\delta(D^2H)_{opt}$ and tree growth reduction factors (growth multipliers) $f1, f2, \ldots, fj$, where the value of each tree growth reduction factor ranges from 0 to 1.

The FORDRY model also considers leaf transpiration, and this depends not only on the meteorological conditions, but also on the tree species. There exist relationships between tree species and ground water level, and tree growth speed and availability of ground water, which were implemented in the model structure. The appropriate model module was created by the following basic water balance equation.

$$\mathrm{W}(t+1) = \mathrm{W}(t) + \mathrm{Prec}(t) - \mathrm{Trans}(t) - \mathrm{Evapor}(t) \quad (4)$$

where:

W(t) – ground water amount in the time period t,
Prec(t) – precipitation,
Trans(t) – transpiration and
Evapor(t) – soil surface water evaporation.

A tree can perish in the following two ways in the FORDRY model: (1) randomly or (2) if it does not reach the minimum diameter increment size. The MORTAL statistical probability for annual tree death is 0.386 (normatively set value; Botkin 1993).

The DRYING block has three basic stages of tree condition: healthy, drying and fallen. A drying tree has the following (dry) parameters, which determines the percentage of dry branches and needles in the crown: 25%, 50%, 75% and 100%. A healthy tree with a dry parameter of 0% has no signs of dryness. In the prediction process, when a tree is classified as dry, its condition changes ('is dry: = true'). From this moment, the tree participates in the process of decline. The DRYING block is responsible for controlling the tree's drying. Fallen tree was presented in the FORDRY model only for three simulation years and after that time the fallen tree was deleted from the model. The DRYING block is a part of mortality stochastic process. This process is random, depending on tree age, growth and climate conditions during the previous year.

The FORDRY model also provides the possibility to define forest felling and planting scenarios. The interface helps to determine the time and sequence of management operations. In addition, the current version of the FORDRY model has improved the appearance of trees and their textures in 3D visualisation, which depicts the stages of shrinkage and decay of tree branches. Throughout the simulation process, changes have been tracked for each tree from its occurrence and annual growth to drying and falling out of the composition of the tree stand.

The current version of the FORDRY model has been verified using historical field data concerning the number of drying trees from permanent plot inventories in 2020. The model represented almost 95–96% similarity with the field data collected in 2020.

Statistical analysis

The statistical Monte Carlo realisations (random simulations including 200 runs under the same starting conditions) were analysed in the FORDRY model. The aim of these Monte Carlo realizations was to present and analyse the general direction of stand statistical dynamics.

Autocorrelation function analysed in the FORDRY model was calculated based on the equation:

$$AC(X,\tau)=\frac{\sum_{t=0}^{t_{\max}-\tau}\left\{\left[X(t)-\overline{X}\right]\cdot\left[X(t-\tau)-\overline{X}\right]\right\}}{\left|\sum_{t=0}^{t_{\max}}\left[X(t)-\overline{X}\right]^{2}\right|}\cdot\frac{t_{\max}}{t_{\max}-\tau} \qquad (5)$$

where:

$AC(X, \tau)$ – the autocorrelation coefficient for X,
X – the parameter for autocorrelation analysis,
$\overline{X}$ – the arithmetic mean for X,
t – time in the model,
τ – time interval.

Results of species biomass and tree number simulations were processed in a statistical program. Statistical analysis was performed with STATISTICA 13 software. Multiple regression analysis for the biomass of spruce, fir, beech and sycamore (*Acer pseudoplatanus* L.) was conducted. The percentage similarity coefficient (Bugmann 1997) was used to compare biomass and tree number of 50 years of simulated data for all permanent plots.

Results

At the beginning of the forecast, the distribution of spruce trees was as follows: 35 trees including six dry specimens on plot 1, 34 including five dry individuals on plot 2 and 25 including five dry individuals on plot 3. At the 10th year of simulation, the number of alive spruce trees decreased compared to the first year of the

Table 2. Stand biomass by tree species for different scenarios in the 50th year of simulation

Species	Scenario				
	control	1	2	3	4
Plot 1					
Fagus sylvatica	101.3 ± 5.6	60.9 ± 3.7	98.5 ± 4.1	109.6 ± 6.1	188.8 ± 6.9
Abies alba	23.8 ± 2.7	10.4 ± 1.1	25.8 ± 2.9	26.8 ± 3.1	51.3 ± 0.9
Picea abies	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
Plot 2					
Fagus sylvatica	103.9 ± 3.4	61.6 ± 1.1	90,1 ± 4.1	105.2 ± 1.8	199.9 ± 6.7
Abies alba	26.4 ± 0.4	11.2 ± 0.2	29.5 ± 0.1	26.9 ± 0.4	50.4 ± 1.6
Picea abies	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
Plot 3					
Fagus sylvatica	108.0 ± 4.6	62.5 ± 3.4	99.6 ± 6.1	110.6 ± 6.1	196.4 ± 6.3
Abies alba	25.8 ± 2.7	12.4 ± 0.9	27.6 ± 3.2	26.8 ± 3.1	52.7 ± 1.2
Picea abies	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1

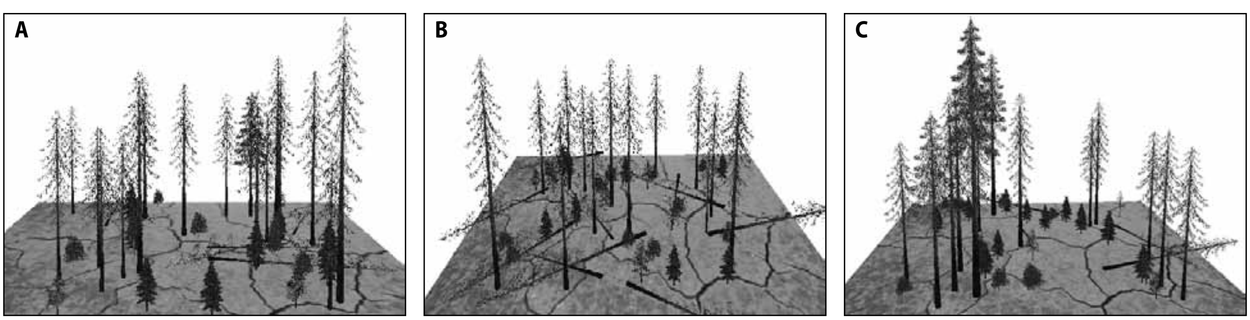

Figure 2. Three-dimensional views of the sample plotsat the 10th year of simulation time(A, B and C – plot nos. 1, 2 and 3, respectively)

simulation period. At the same time, the numbers of dry and fallen spruce trees increased. Forecast within the control scenario provided the following views of the plots stand at the 10th year (Fig. 2) of simulations.

The simulation showed a clear trend in decreasing of spruce biomass up to 50th year for all permanent plots (Tab. 2), both for control and for all other scenarios. Dead spruces were replaced by naturally regenerating beech and fir trees. In the control scenario for the 50th year, the biomass of beech was slightly higher than 100 $t \cdot ha^{-1}$ on all permanent plots. In the first scenario, the biomass of beech was 1.7 times smaller on all plots in comparison to control. In the second scenario, the biomass of beech decreased by 1.1 times on plots 1 and 3 and by 1.2 times on plot 2. In the third scenario, the biomass of beech increased by 1.1 times on plot 1 and was at the same level on plots 2 and 3. Only in the fourth scenario, the biomass of beech increased by 1.9 times on plots 1 and 2 and by 1.8 times on plot 3 in comparison to control. The biomass of fir decreased more than 2 times in the first scenario and slightly increased in the second and third scenarios (Tab. 2). In the fourth scenario, the fir biomass increased 2 times in comparison to control.

Statistical (coefficient of percentage similarity) comparison between plots 1 and 2 and also between

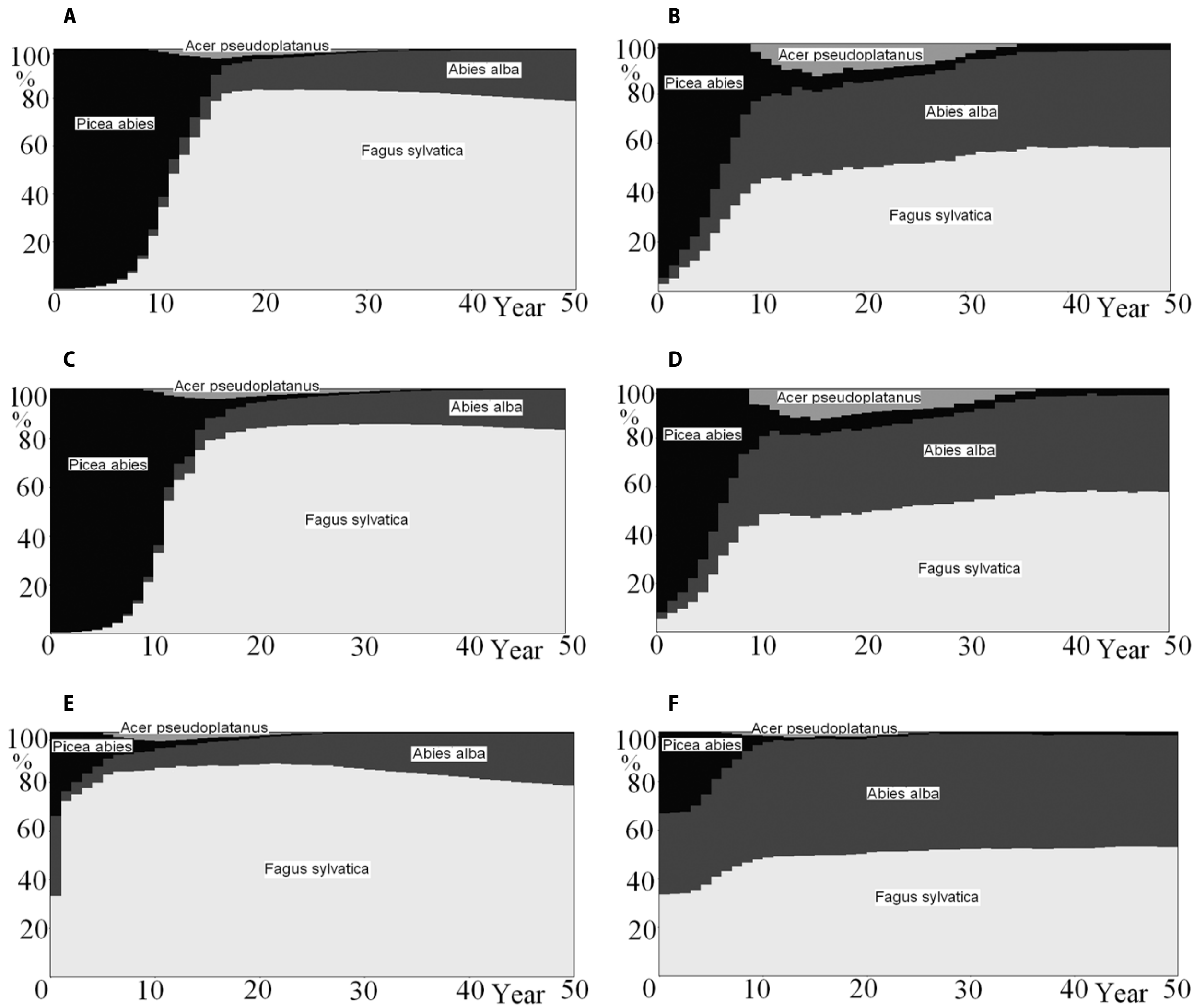

Figure 3. Temporal changes in the share of biomass (left panel) and the number of trees (right panel) in control (A, B) and in the first (C, D) and fourth (E, F) scenarios for plot 2

plots 2 and 3 showed very high similarity values in the range of 0.97–0.98 for total biomass and 0.98–0.99 for the number of trees. This was the reason for choosing only one plot (2) for graphical presentation.

In the Monte Carlo statistical realisation, the permanent plot 2 representedthe decline of spruce stands in the Nadsyansky Regional Landscape Park. The biomass and number of spruce trees decreased. Generally, in all scenarios in the subsequent years of simulation, the proportion of spruce regarding the tree number was slightly higher than the biomass after 15th year of simulation. The proportion of beech biomass was much higher than the proportion of beech trees' number. The proportion of fir and sycamore trees number was much higher (Fig. 3B, 3D, 3F) than the proportion of fir and sycamore biomass (Fig. 3A, 3C, 3E), as it is presented in the control, first and fourth scenarios.

Only in the first scenario, the proportion of beech trees' biomass was slightly higher (Fig. 3C) compared to control (Fig. 3A) in the 50th year of simulation time. In the second scenario, decrease in biomass and trees' number of spruce was not interrupted. After cutting all trees in the third scenario, the biomass of spruce trees was not dominated. Even in the fourth scenario, after planting spruce, fir and beech trees in a similar proportion, the spruce biomass (Fig. 3E) and tree number

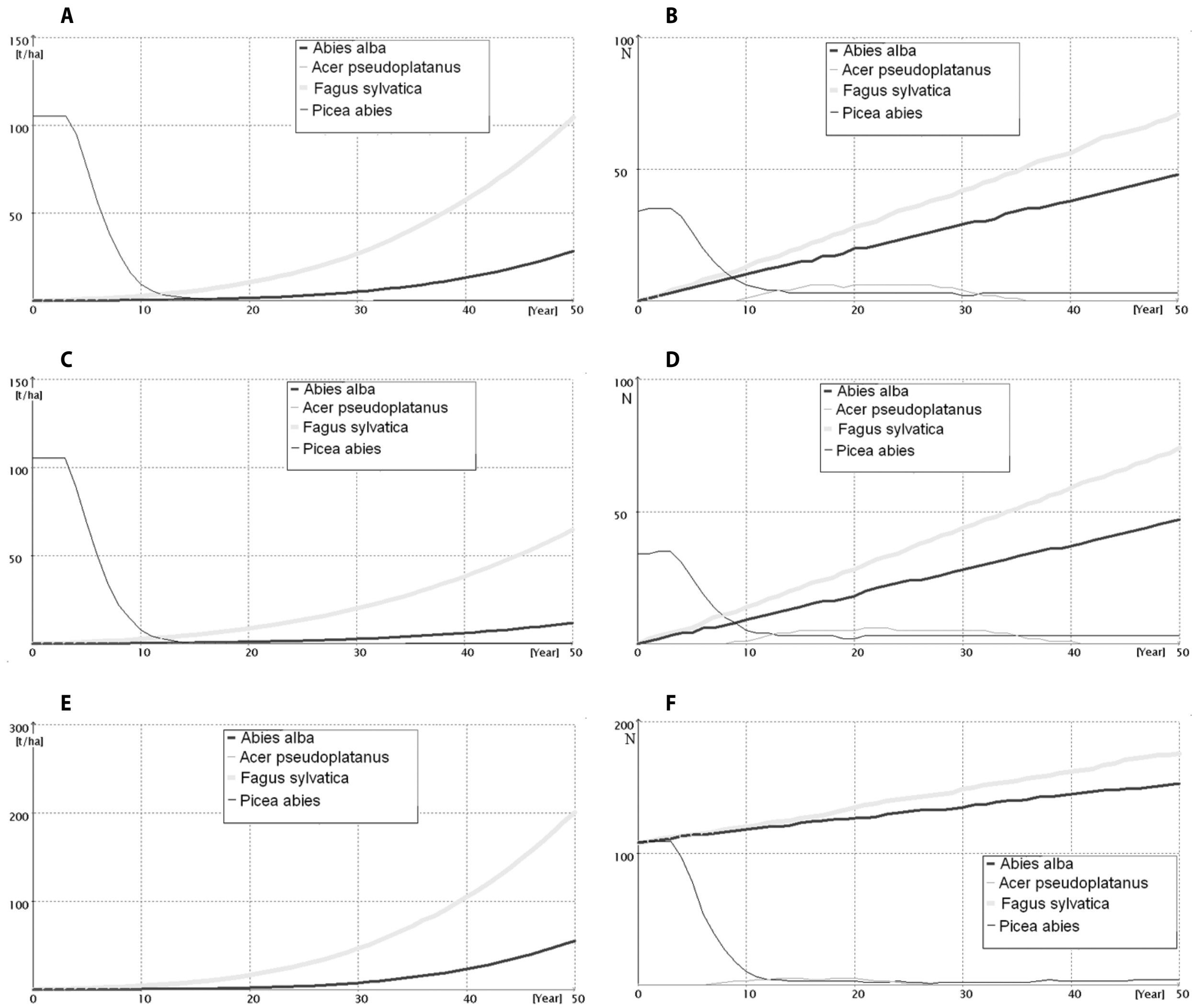

Figure 4. Prediction of biomass (left panel) and number of trees (right panel) in control (A, B), in the first (C, D) and fourth (E, F) scenarios for plot 2

(Fig. 3F) decreased. Number of sycamore trees was lesser compared to control and the first scenario. Number of beech and fir trees showed an opposite trend to spruce, that is, the number increased (beech, fir and sycamore trees were absent in the permanent plot at the beginning of simulation).

In the Monte Carlo statistical realisation for the control scenario, the FORDRY model predicted (on plot 2) a decrease in spruce biomass from 104.7 ± 4.6 $t \cdot ha^{-1}$ (Fig. 4A) at the beginning of simulation to 0.3 ± 0.1 $t \cdot ha^{-1}$ and an increase in beech biomass (up to 103.9 ± 3.4 $t \cdot ha^{-1}$) and fir biomass (up to 26.4 ± 0.4 $t \cdot ha^{-1}$) in the 50th year. The number of trees increased to 69 individuals for beech and 48 for fir trees. The number of spruce trees decreased to five individuals in the 12th year of simulation period and remained at the same level until the end of simulation (Fig. 4B). In the middle of the simulation period, the number of sycamore individuals changed from five to seven.

The first scenario showed a similar trend in the decline of spruce forests (up to 0.2 ± 0.1 $t \cdot ha^{-1}$) and an increase in beech and fir biomass. However, biomass was smaller (Fig. 4C) for beech (61.6 ± 1.1 $t \cdot ha^{-1}$) and fir (11.2 ± 0.2 $t \cdot ha^{-1}$) in the 50th year in comparison with control. The FORDRY model predicted that the number of trees in this scenario (Fig. 4D) was similar to control (Fig. 4B).

In the second and third scenarios, biomass and number of spruce trees continued to decrease. In the second scenario, the biomass of beech was about 13.3% smaller than in control and the biomass of fir was about 11.7% greater than in control. In the third scenario, the biomass of trees increased in the 50th year (1.3–1.9%) in comparison with control.

Only in the fourth scenario, the model predicted a possible effective increase (1.9 times) in beech (Fig. 4E) and fir (2.2 times) biomass compared to control in the 50th year of simulation period. The number of trees increased to 169 individuals for beech and to 152 for fir (Fig. 4F). The number of spruce trees decreased to five individuals in the 50th year of simulation period. In the middle of the simulation period, the number of sycamore individuals (Fig. 4F) was minimal (changed from two to seven) and was not visible on the figure for biomass (Fig. 4E).

Maximum number of spruce trees died during the period from 3rd to 18th year of simulation time in control (Fig. 5A) and in the period from 3rd to 20th year in

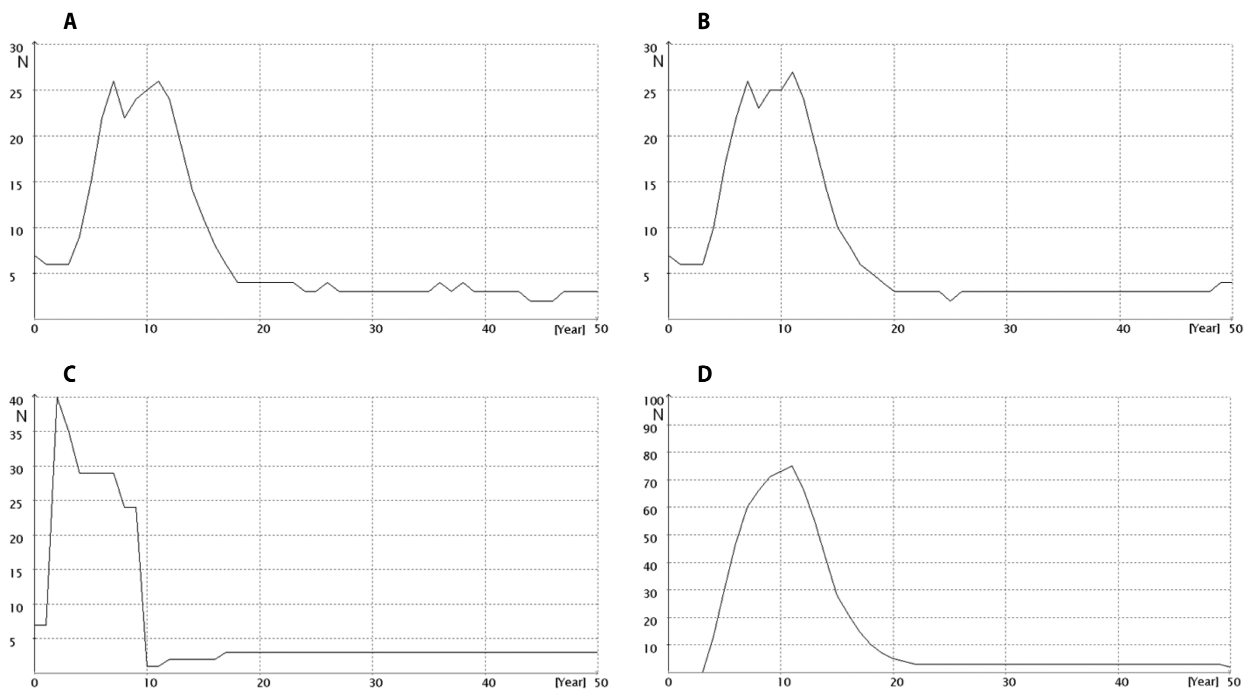

Figure 5. Number of dead trees in the simulations conducted for plot 2 (A – control, B – first scenario, C – third scenario, D – fourth scenario)

the first scenario (Fig. 5B). After the 20th year, dying of spruce was at the level of 3–4 individuals.

In the third scenario, when the maximum number of spruce trees was cut in the first year of simulation, dying of spruce trees continued up to 10th year (Fig. 5C). After that, spruce dying stayed at the level of three individuals.

In the fourth scenario, the maximum number of spruce trees died from 3rd to 20th year of simulation time and after that stayed at the level of two individuals (Fig. 5D).

Statistical analysis showed that in the control scenario the auto-correlation of spruce in terms of biomass changed from strong positive (+0.9) to weak negative(–0.1) (τ = 3 at a level more than +0.75) (Fig. 6A). The auto-correlations for beech (Fig. 6B) and fir (Fig. 6C) were stronger in comparison to spruce (at a level more than +0.75 τ = 5.8 for beech and τ = 4.5 for fir). Also, the auto-correlations for sycamore (Fig. 6D) compared to spruce were stronger (at a level more than +0.75 τ = 6.3). The auto-correlation of spruce concerning tree number was slightly positive than in terms of biomass. Generally, the auto-correlation of spruce concerning biomass and number of trees did not show significant changes in the first scenario compared to control (τ = 2 at a level more than +0.75).

In the second and third scenarios, the auto-correlations of spruce in terms of biomass and number of trees decreased (from weak positive to weak negative). Only in the fourth scenario, the auto-correlations of spruce in terms of biomass and number of trees increased (were strong positive at a level more than +0.75 for τ = 4).

In the control scenario, the cross-correlation between spruce and beech biomass was negative and changed from –0.42 to –0.59 (Fig. 7A). The cross-correlation between spruce and fir was also negative and changed from –0.38 to –0.61 (Fig. 7B). This result suggests that the relations between spruce and beech and between spruce and fir were competitive. The cross-correlations between spruce biomass and total stand community biomass (Fig. 7C) decreased (from moderate positive [+0.43] to strong negative [–0.76]). Cross-correlations between the number of spruce trees and total stand density changed from moderate negative (–0.46) to strong negative (–0.75) for τ = 8 and to

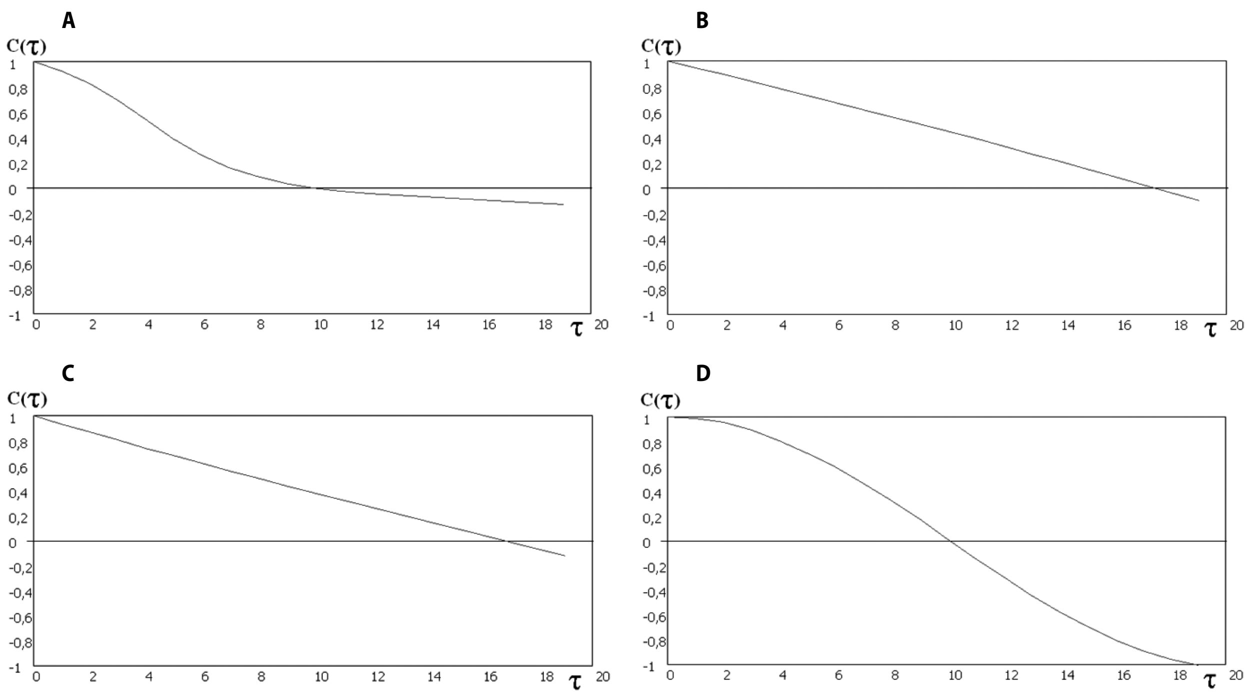

Figure 6. Auto-correlation of biomass in control conditions for spruce (A), beech (B), fir (C) and sycamore (D) (τ – Kendall coefficient)

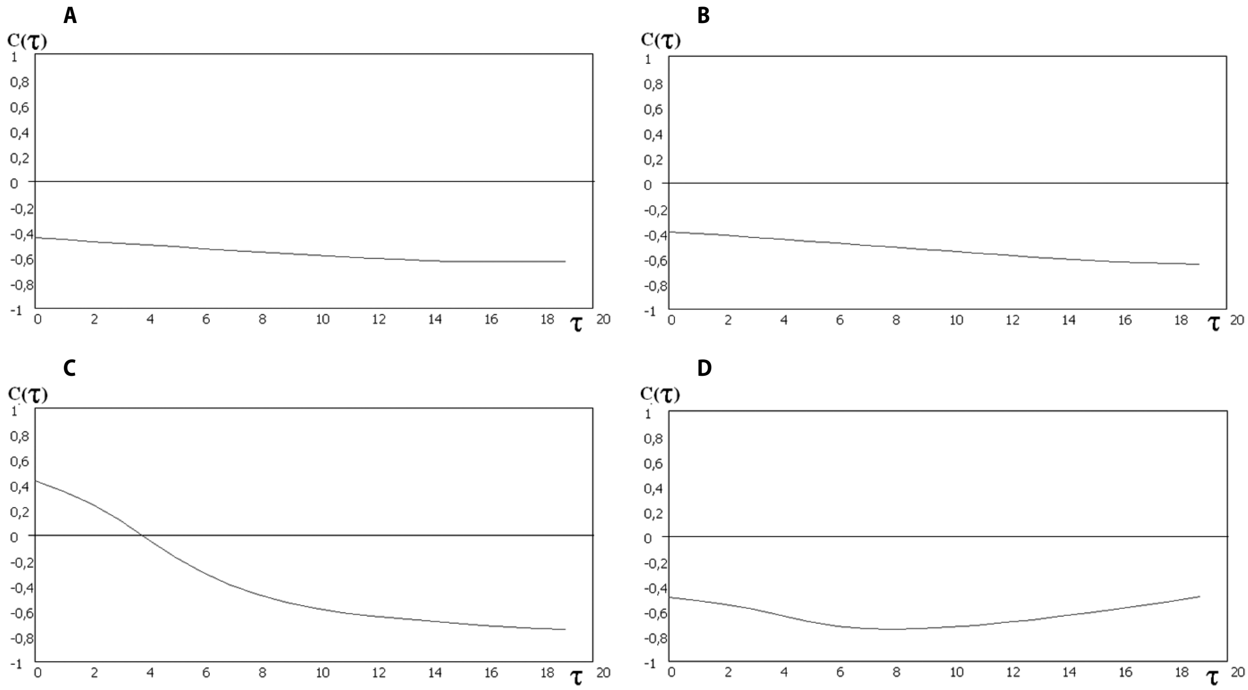

Figure 7. Cross-correlations in the control scenario: between spruce and beech biomass (A), between spruce and fir biomass (B), between spruce and total stand biomass (C), between spruce tree number and total stand density (D) (τ – Kendall coefficient)

–0.42 for τ = 18 (Fig. 7D). This suggests that spruce has a little influence on total stand community, which was also confirmed in the first, second, third and fourth scenarios.

Discussion

The transformation of forest stands has been mainly analysed as a change of structure (Schützet et al. 2006). During the 19th century, in the Ukrainian Carpathians native beech and mixed forests had been replaced, for economic reasons, by pure spruce stands, which were not native in the region (Parpan et al. 2014; Stoiko 1999). Severe timber harvesting in 1950–1960 resulted in a current strong unbalance in forest age structure, drastic decline of biological and landscape diversity and disturbance of hydrological regime in the Carpathians (Shparyk 2017, 2019).

Nowadays, under changing climatic conditions and increasing human pressure, such modified forest ecosystems have been rapidly losing their vitality and resistance against abiotic and biotic impacts. Conversion of man-made even-aged spruce stands into mixed uneven-aged ones is internationally thought as an urgent and efficient solution of the problems posed by a former yield-oriented forest management and by current climate change (Lavnyy and Schnitzler 2014).

This analysis presents the perspectives for the application of FORDRY computer model in the prognosis of spruce forests' decline and their transformation. The FORDRY model includes a recently created and constantly developed module of forest drying. As a result, it is possible to simulate the potential changes caused by declining, and thus to predict the impact of this disturbance agent on forest conditions and stand regeneration by conducting simulations on the issues concerned. The FORDRY model uses both general mathematical relationships functioning within a forest ecosystem and empirical ones characteristic for tree stands occurring on analysed plots. That is, it combines ecological models as well as empirical ones (Brzeziecki 1999; Bugmann 2001; Kozak et al. 2014).

The results obtained suggest that even small climate changes, especially in air temperature, can cause a decrease in biomass and tree number of spruce and an increase in number of fir and beech trees. It is consistent with the data presented in literature. For example, Debrynuk (2011) and Shparyk (2019) reported that in connection with climate changes, the declining of spruce forests in the region will continue. FORDRY model simulationsprovided similar results – regional forests have lost spruce trees up to 50th year. The best growing conditions were for beech and fir. However, according to the simulations of spruce forest transformation, it is possible to introduce native species into declining forest stands, which can provide the highest stability and productivity of the forests.

Unfortunately, in the Western European countries there were only small remains of natural (primary) forests. In this context, virgin forests of the Ukrainian Carpathians and the studies conducted in these forests are extremely important for the primary forestry management throughout Europe. One of the examples of this management and renovation methods is our analysis in the FORDRY model, showing tendency of decline of man-made even-aged spruce forests. The area of such forests is constantly increasing in the Ukrainian Carpathians. For this reason, computer simulation using the FORDRY model is very perspective. The model predicted decreases of spruce biomass and number of trees in the control and all scenarios in the example of Nadsyansky Regional Landscape Park. This tendency, once again, emphasises the relevance of introducing sustainable forest management methods that increase the sustainability of forests. It was confirmed (Parpan et al. 2014; Shparyk 2014) that secondary spruce forests' decline is very intensive in the Ukrainian Carpathians. Excessive distribution of decline of spruce stands and deterioration of the stability of spruce forests along with a decrease in the growth of spruce biomass require emergency management activities based on forest typology, forest monitoring results and on their economic analysis (Shparyk 2017). The benefits of spruce stand transformation have an impact on increasing their productivity and biomass, improving soil conditions and biodiversity and improving resistance to declining, which was already presented in the literature (Prescott 2002; Pretzsch et al. 2010; Shparyk 2019).

Conclusion

A simulation of various forest management scenarios using the FORDRY model showed the need to change approaches to forest managementin Nadsyansky Regional Landscape Park in the Ukrainian Carpathians in order to restore local forests. It is possible to transform declining spruce forests into stable native mixed stands (beech and fir) for a period of 40–50 years.

Passive (existing) forest management will destroy regional spruce forest under the actual climate conditions (control) and in the first scenario – in the following 50 years. Beech and fir can replace spruce in regional forests in Nadsyansky Regional Landscape Park.

Active forest management will also give a chance to transform secondary and declining spruce forests into their native structure: cutting dry trees (second scenario) will not change destroying of spruce forests; cutting all tress (third scenario) will transform their structure and planting (fourth scenario) showed possibilities for the highest forest biomass re-establishment. Therefore, prognosis results are a base for optimal forest management planning – combination of cutting and planting scenarios provides an effective transformation of declining spruce forests in stable native stands with a biomass of beech 200, fir 50 and spruce 0.3 $t \cdot ha^{-1}$ in the 50th year of simulation time. It is necessary to use resistance in this type of forest tree species (mainly beech and fir) for planting.

Further scientific studies of spruce forests' decline should be based on investigations of their health condition and on forecasting with the use of computer simulation software. The FORDRY model provides the chance for estimating the development of stages of spruce stands' decline in any forest type.

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