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Forecasting drying up of spruce forests in Transcarpathia (Ukraine) using the FORKOME model

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Abstract: This paper presents the results of analysis of drying up of spruce stands obtained by the use of the FORKOME computer model. The verification of this model was conducted with field data from spruce-dominated mixed forests in Transcarpathia (Ukraine). The forecast of drying up, based on the latest version of the simulation of FORKOME computer model, allowed to evaluate results regarding bioclimatic effects on the displacement, growth, survival and death of spruce and other tree species. The modelling was performed on the basis of statistical Monte Carlo simulations. The forecast of the spruce stand dynamics was conducted for 100-year period along with control and warm-dry scenarios. The analysis has revealed the rapid decrease of biomass in the first decade as a result of spruce decline. Auto-correlation analysis of spruce and cross-correlation analysis of the relation between tree species were conducted as well.

Keywords: dynamics; biomass; number of trees; simulation

Nowadays, under changing climatic conditions, modified forest ecosystems are rapidly losing their vitality and resistance against destructive abiotic and biotic impacts (Spiecker et al. 2004). Spruce mortality was recorded in different regions evenly across all slope expositions (Mandre et al. 1992). The infestation intensity slightly increased with the spruce representation in stands and was higher in stands older than 80 years (Grodzki et al. 2014).

At the present time, a decline of spruce forests is made visible on the area of 19,300 ha of forests in the Ukrainian Carpathians (3% of all spruce stands) with the wood volume of 5.8 million m^3 (Parpan et al. 2014). Studies of the decline of spruce forests concerned the Ukrainian Carpathians (Debrynuk 2011; Turis, Shanta 2013; Lavnyy, Schnitzler 2014). Simulation of conversion strategies for 62-year even-aged secondary spruce stand located in the Transcarpathian region of the Ukrainian Carpathians using the SIBYLA growth simulator (Fabrika 2005) was conducted.

One of the reasons for drying up of spruce forest is climate warming. Forests are particularly vulnerable to climate change, because the long lifespan of trees does not allow for their quick adaptation to environmental changes (Linder et al. 2010). Due to climate change, there is a number of factors affecting forest ecosystems that can function independently or in combination. These factors are temperature changes and rainfall. The occurrence

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of meteorological phenomena, although these are natural processes occurring in the atmosphere, negatively affects forests, causing very dangerous consequences (Durlo 2011).

The forecasting of the dynamics of spruce forest drying up requires the use of special tools, i.e. properly designed computer models. As a result, an attempt was made to use the FORKOME model to carry out prognostic simulations of possible changes of factors affecting spruce mortality. Autocorrelation and cross-correlation functions were added to the FORKOME model and can also be considered as coefficients of mutual influence (Jørgensen 1994). The analysis of the relations (correlations) between drying up of spruce and other tree species in the forest stands is quite interesting.

Taking into consideration the above-mentioned, the main objective of this paper is to perform the forecasts of biomass and tree number in drying up spruce stands in control conditions (actual temperature and precipitation) and in warm-dry scenario. The additional aim of this work is to present the results of investigation into correlation analysis between tree species in the drying up forest stands using the FORKOME computer model, and to indicate the number of trees and biomass dynamics in 100-year prognosis in spruce-dominated mixed forests in the Transcarpathian region (Ukraine).

MATERIAL AND METHODS

The study was conducted in two permanent research plots (PRP) that are situated in the Lazenshchyna forest area in Jasinski forest district in Transcarpathia.

PRP 1 is located in compartment 26, subcompartment 62 (48°11'10.4"N, 24°29'04.2"E) at the altitude of 1,350 m a.s.l. in the type of forest growth conditions (FGC) "spruce forest on wet soils".

PRP 2 is located in compartment 25, subcompartment 20 (48°12'50.9"N, 24°29'27.2"E) at the altitude of 1,000 m a.s.l. in the type of FGC "fir-beech-spruce forest on wet soils".

The brown soil covering the Carpathian flysch is characteristic of those plots. Tree species composition consists of spruce (*Picea abies* [L.] Karsten), fir (*Abies alba* Mill.) and sycamore maple (*Acer pseudoplatanus* L.) trees. The diameters ($DBH_{1.3}$), heights (*H*) and age are presented in Table 1.

Research plots were located on the northern slope of the mountain (inclination of 20°–25°). Each of the plots had a square shape with a side of 25 m (625 m^2). Such a size is often used in gap models (Bugmann 2001). After conducting 200 test simulations for each study plot, it was found that the analysed area corresponded to the area of 200 × 0.0625 = 12.5 ha.

All trees in the analysed plots were numbered and their DBH, height, crown radius, age, as well as *X* and *Y* coordinates were recorded. All data collected on the study plots were entered into the FORKOME model (Kozak et al. 2007, 2012). Stand development simulations were carried out over a period of 100 years.

The FORKOME model was already analysed in details in previous publications (Kozak et al. 2007, 2012), therefore only a brief description of the model regarding the drying process is presented in this publication.

The "Drying" block has been added to the FORKOME model. This block is responsible for controlling the drying up of trees. There are three basic states of a tree: healthy, drying and overthrowing. A healthy tree with a drying value of 0% has no signs of decline. Drying trees have the "dry" parameter which determines the percentage of drying in the crown: 25%, 50%, 75% and 100%.

Drying block is a part of the mortality stochastic process. This process is random, depending on tree age, growth and dry conditions during the previous year.

Table 1. Basic characteristics of the trees on permanent research plots (PRP): PRP 1 and PRP 2

PRP	Species	DBH (cm)			*H* (m)			Age (years)			*N*
		mean	min	max	mean	min	max	mean	min	max	
1	*Picea abies*	34.5	11.1	72	22.9	9	34.5	78	28	106	30
1	*Acer pseudoplatanus*	22.2			17			68			1
2	*Picea abies*	25.2	8.6	42.3	20.5	8	28	59	21	82	60
2	*Abies alba*	29.0	10.9	41.6	21.5	11	28	61	28	81	12
2	*Acer pseudoplatanus*	31.8			28			74			1

DBH – diameter at breast height, *N* – number of trees

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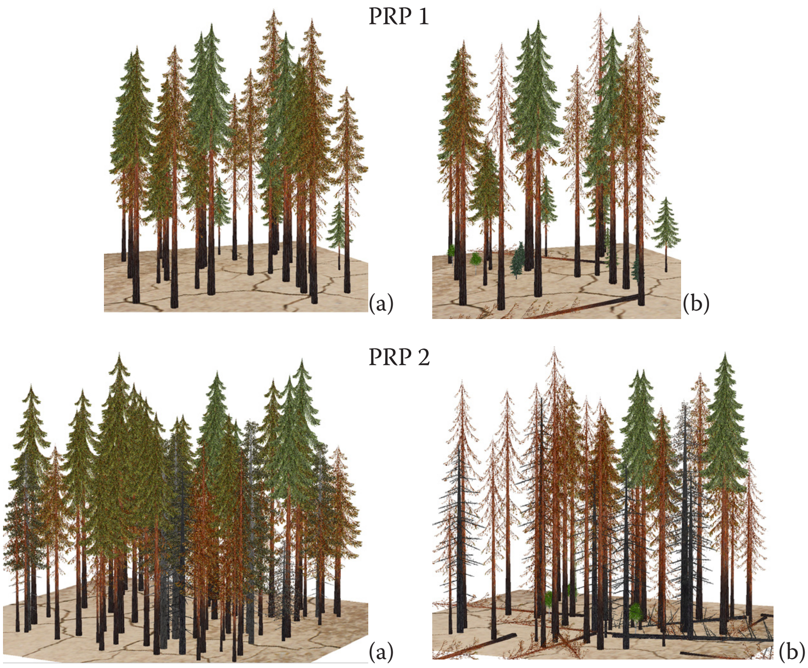

Fig. 1. View of permanent research plots (PRP): PRP 1 and PRP 2 at the beginning (a), in the 6^{th} year of the forecast (b) in FORKOME model interface

Reproduction simulation is also a stochastic process depending on saplings of species, surface conditions of light and mean temperature of litter layer. The amount of seeds and saplings is distributed randomly and restricted by available ground level light. The amount of saplings is generated separately for each type of light tolerance of tree species, according to their light tolerance: light tolerant, medium tolerant and shadow tolerant. In FORKOME the light radiation loss is calculated. This loss is caused by the total shading by the leaf area of higher trees.

Auto-correlation and cross-correlation functions are included to improve the sensitivity analysis of forest ecosystems. The number of trees and their biomass are important parameters in these calculations.

The current version of the FORKOME model has been verified on the data from 2014 and 2016. After running the model from 2010, the forecast results for the years 2014 and 2016 were verified with field data. The model represented almost 90% similarity with field data for 2014 and 87% similarity with field data collected in 2016.

Forecasts of biomass and number of trees in drying up spruce stands were conducted in control actual conditions (temperature 1,450°C degree-days and precipitation 700 mm), in warm-dry scenario (with increase of 200°C degree-days and decrease of 200 mm precipitation from the first year of simulation) and in cold-wet scenario (with decrease of 200°C degree-days and increase of 200 mm precipitation from the first year of simulation). Results obtained for the control were compared with results for warm-dry scenario and opposite cold-wet scenario. An additional aim was to conduct a correlation analysis for the drying up forest stands.

RESULTS

General view (Fig. 1) of PRP 1 and PRP 2 at the beginning (a), in the 6^{th} year of the forecast (b) in FORKOME model interface are presented.

On PRP 1 in Monte Carlo realization (200 simulations) for the control conditions the FORKOME model predicted that the biomass of spruce trees decreased from 292 $t\cdot ha^{-1}$ in the first year to 26.4 ± 2.2 $t\cdot ha^{-1}$ in the 10^{th} year of simulation (Fig. 2a). After reaching the minimum biomass, spruce biomass will increase to 63 ± 6.4 $t\cdot ha^{-1}$ in the 100^{th} year. The model predicted also an increase of fir (to 180 ± 4.6 $t\cdot ha^{-1}$) and beech (to 195 ± 5.6 $t\cdot ha^{-1}$) biomass in the 100^{th} year of simulation. In the control scenario the model showed an increase in the number of trees of fir (to 90 individuals) and beech (to 86 individuals). After a decrease in the number of spruce trees from 30 individuals in the first year of simulation to 10 individuals in the 10^{th} year of simulation (Fig. 2b), the spruce numbers increased to 44 individuals in the 100^{th} year of simulation (Fig. 2a; Table 2). The number of trees re-

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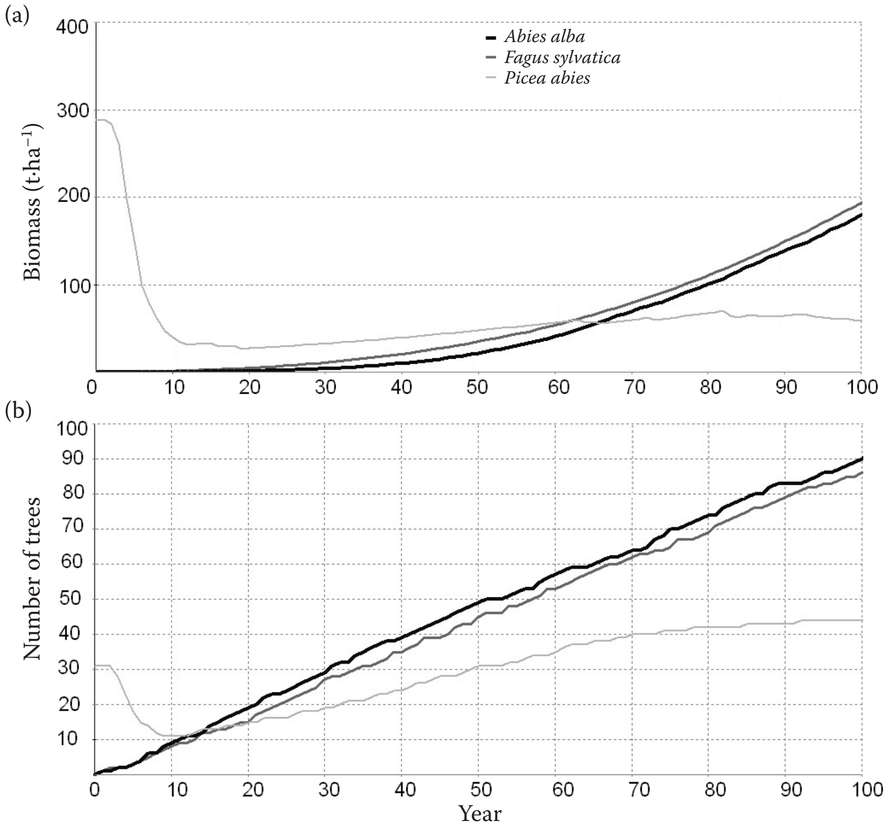

Fig. 2. PRP 1 in control scenario: (a) biomass, (b) number of trees

generating per year (height of trees was more than 1.30 cm) equalled 0.9 for fir and 0.86 for beech. The regenerating tree indicator per year equalled 0.38 for spruce from 10^{th} to 100^{th} year of simulation.

Maximum drying up of spruce trees is presented at the beginning of simulation (Fig. 3). Percentage of drying trees, which is determined by the percentage of drying in the crown, was as follows: 25% up to 9^{th} year of simulation (Fig. 3a), 50% up to 11^{th} year of simulation (Fig. 3b), 75% up to 15^{th} year of simulation (Fig. 3c), 100% up to 22^{nd} year (Fig. 3d).

The number of healthy trees increased for all species (Fig. 4). However, spruce regeneration was lower compared to fir and beech at the end of simulation.

On PRP 2 in Monte Carlo realization for the control conditions the model predicted that the biomass of spruce trees decreased from 290 t·ha^{-1} in the first year of model time to 3.4 ± 1.2 t·ha^{-1} in the 12^{th} year of simulation. After reaching the minimum biomass, spruce biomass will be at the level 5.3 ± 1.6 t·ha^{-1} in the 100^{th} year. The model predicted also an increase of fir (to 182 ± 5.6 t·ha^{-1}) and beech (to 98 ± 4.3 t·ha^{-1}) biomass

Table 2. Prediction of the number of trees on PRP 1 in control, warm-dry and cold-wet scenarios in 0, 10, and 100 years of simulation

PRP	Species	Scenarios (simulations in years)								
		control			warm-dry			cold-wet		
		0	10	100	0	10	100	0	10	100
1	*Picea abies*	30	10	44	30	7	1	30	14	46
1	*Abies alba*	0	9	90	0	4	90	0	9	81
1	*Fagus sylvatica*	0	10	86	0	5	67	0	9	64
1	*Acer pseudoplatanus*	1	0	0	1	1	43	1	0	0
2	*Picea abies*	60	5	40	60	4	3	60	9	43
2	*Abies alba*	12	5	78	12	11	28	12	28	81
2	*Fagus sylvatica*	0	5	99	0	10	71	0	7	70
2	*Acer pseudoplatanus*	1	1	14	1	2	30	1	0	0

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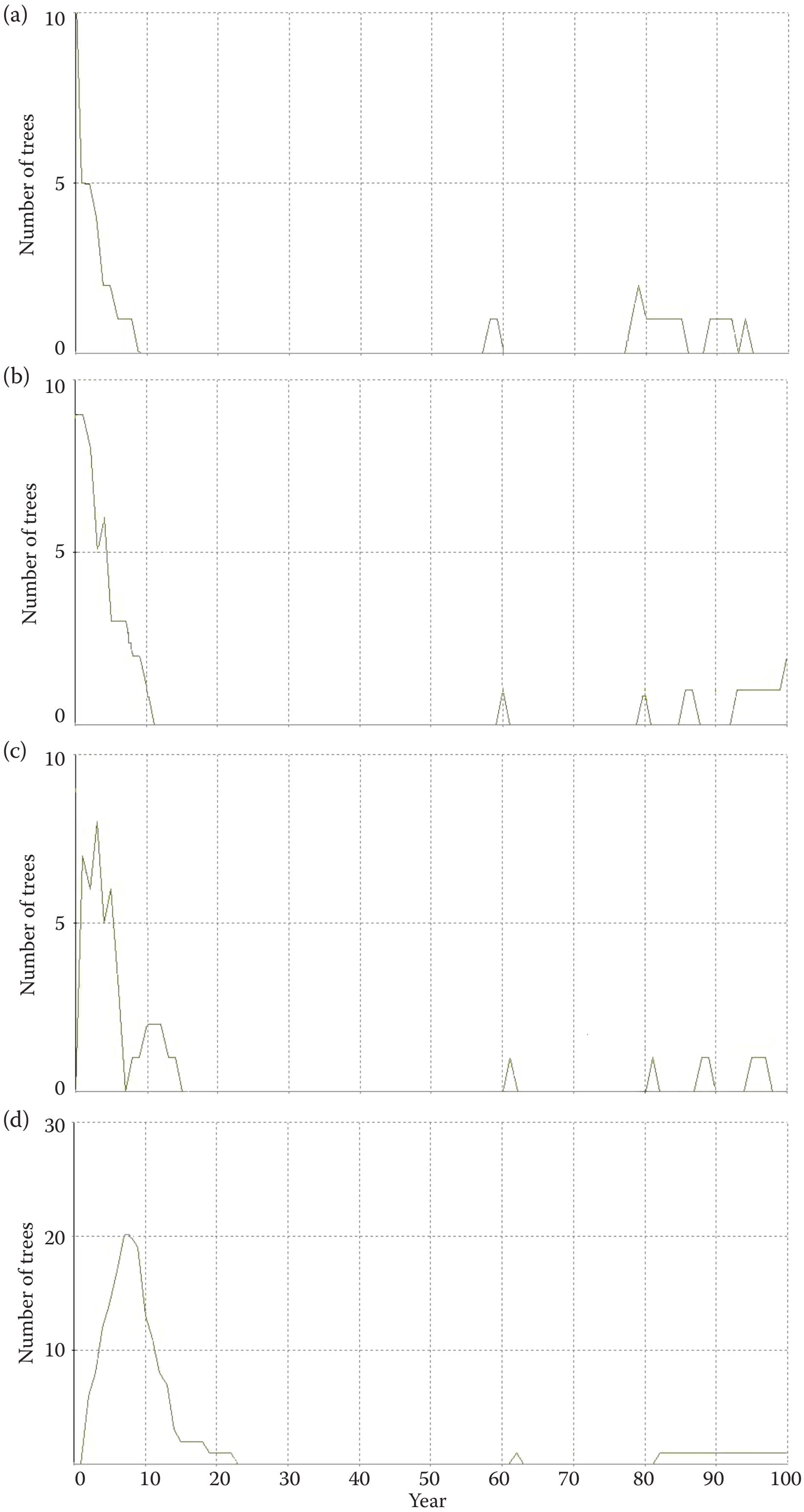

Fig. 3. Prediction of drying spruce trees in control scenario on PRP 1: (a) 25%, (b) 50%, (c) 75%, (d) 100% dry trees

in the 100th year of simulation. The model showed an increase in the number of trees of fir (to 78 individuals) and beech (to 99 individuals). After a decrease in the number of spruce trees from 60 individuals in the first year of simulation to 5 individuals in the 10th year of simulation, the number of spruces increased (Table 2). The number of sycamore maple trees increased to 14 individuals in the 100th year. The regenerating tree indicator per year equalled 0.81 for fir and 1.0 for beech. After active mortality (5.5 individuals per year from 0 to 10 years) the regeneration per year for spruce was 0.39 from 10th to 100th year of simulation.

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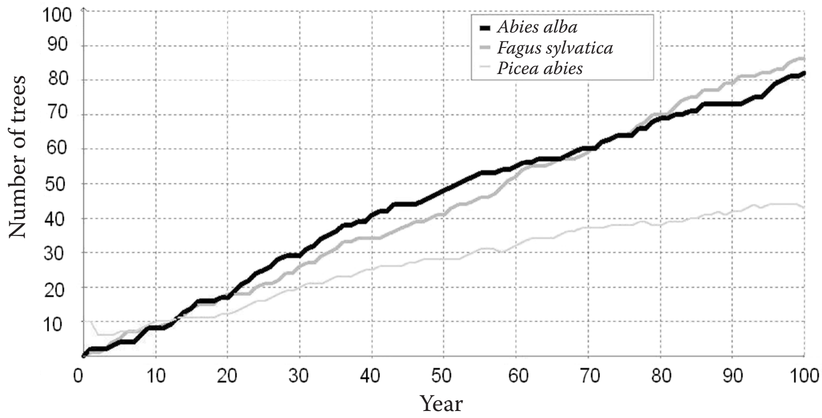

Fig. 4. Prediction of healthy trees in control scenario on PRP 1

The FORKOME model predicted that biomass of spruce trees decreased to zero in the warm-dry scenario for both plots. After reaching the minimum biomass, spruce biomass will be at the minimum level of 2.3 ± 0.6 t·ha^{-1} in 100 years. The biomass of beech will change to 80 ± 4.4 t·ha^{-1} on PRP 1 and to 62 ± 0.7 t·ha^{-1} on PRP 2 in 100 years. The model predicted an increase in the number of fir trees (to 88 individuals) and beech trees (to 90 individuals) in 100 years and a decrease in the spruce number (from 30 individuals on PRP 1 and from 60 individuals on PRP 2 in the first year of model time to 4–7 individuals in the 100th year). The number of sycamore maple trees increased to 43 individuals on PRP 1 and to 30 individuals on PRP 2 in the 100th year. In the warm-dry scenario the number of spruce trees regenerating on PRP 1 and on PRP 2 decreased compared to control conditions.

In the cold-wet scenario the number of spruce trees on PRP 1 and on PRP 2 decreased from the beginning of simulation to the 10th year and subsequently increased to the 100th year of simulation time (Table 2). In the cold-wet scenario the results of biomass and number of spruce trees show less dramatic changes compared to the results in the warm-dry scenario. The number of spruce trees in the cold-wet scenario was higher than in the control in the 10th and 100th year of simulation.

Data concerning spruce biomass and spruce tree number were analysed from the correlation point of view in FORKOME model simulations in control and in warm-dry scenario on PRP 1 the strong auto-correlation on the level from 0.75 to 1.0 was visible up to $\tau = 10$ for the number of trees and only to $\tau = 2$ for biomass (Fig. 5a). The strong auto-correlation (more than 0.75) was only up to $\tau = 2$ for biomass and to $\tau = 4$ for the number of trees on PRP 2 (Fig. 5b). The auto-correlation of spruce in terms of the number of trees is stronger than that for biomass for both plots.

The cross-correlation between spruce biomass and fir biomass is weak (less than –0.20 for PRP 1; Fig. 6a) and moderate (from 0.4 to –0.4 for PRP 2; Fig. 6b). It confirms the lack of a strong correlation between spruce and fir biomass. The strong correlation on the level higher than 0.75 for the indicator $\tau = 12$ is only between the spruce and fir number of trees on PRP 1 (Fig. 6a).

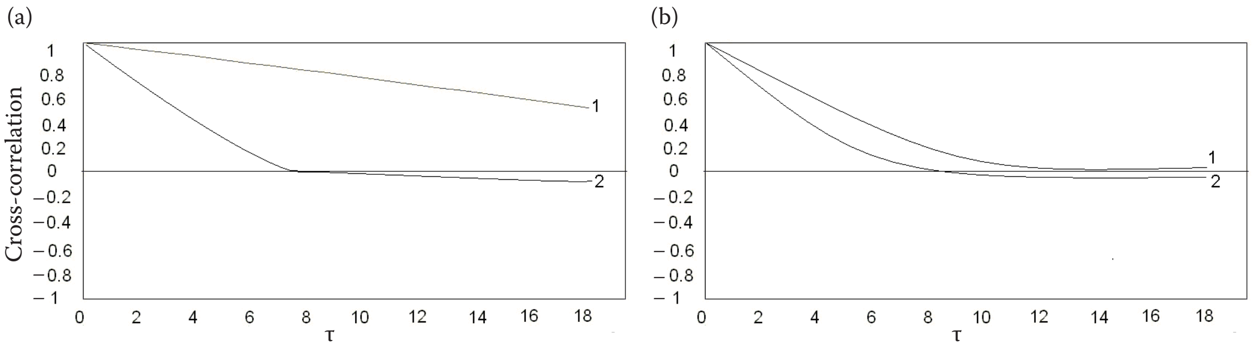

Fig. 5. Auto-correlation of spruce number of trees (1) and biomass (2) on PRP 1 (a) and PRP 2 (b), (τ – Kendall coefficient)

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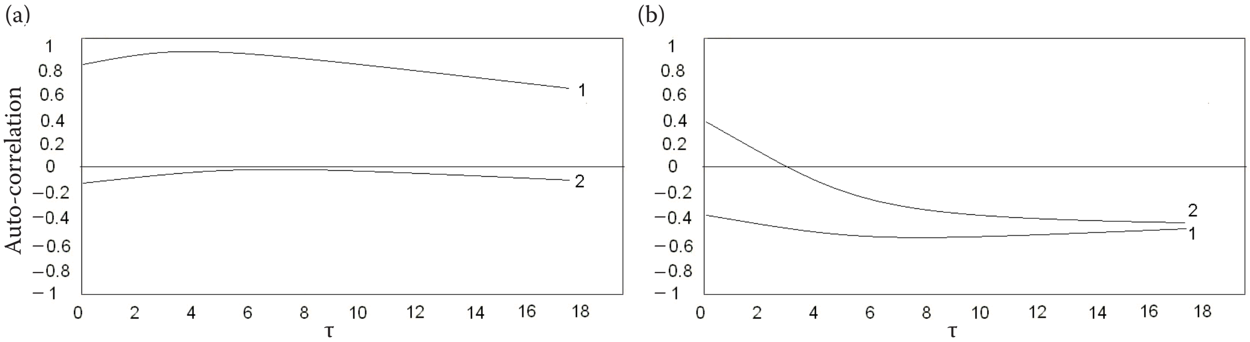

Fig. 6. Cross-correlation between the spruce and fir number of trees (1) and biomass (2) on research plots PRP 1 (a) and PRP 2 (b)

A weak cross-correlation between spruce biomass and total tree stand biomass and also between spruce tree number and tree number of the whole stand community was observed. That confirms a weak influence of spruce on the whole stand community on analysed plots.

In the warm-dry conditions the auto-correlation of spruce, concerning the number of trees on PRP 1 (Fig. 7a), was weak in comparison with control scenario. On PRP 1 auto-correlation in terms of the number of trees and auto-correlation regarding biomass in the warm-dry scenario were similar to the auto-correlations for PRP 2 (Fig. 7b). It means that in this warm-dry scenario the correlations on PRP 1 (1,350 m. a.s.l.) will be similar to the correlations on PRP 2 (1,000 m a.s.l.) in control conditions.

The auto-correlation of fir and beech is stronger (on the higher level than 0.75 up to τ = 8 for biomass) compared to the auto-correlation of spruce for PRP 1 and PRP 2 in warm-dry climate change scenarios.

In warm-dry climate change scenarios the cross-correlations between spruce and fir for biomass and for the number of trees for PRP 1 are negative and changed from –0.5 to –0.6 for the number of trees (Fig. 8a) and from –0.2 to –0.3 for biomass. It can mean that in this climate scenario the relation be-

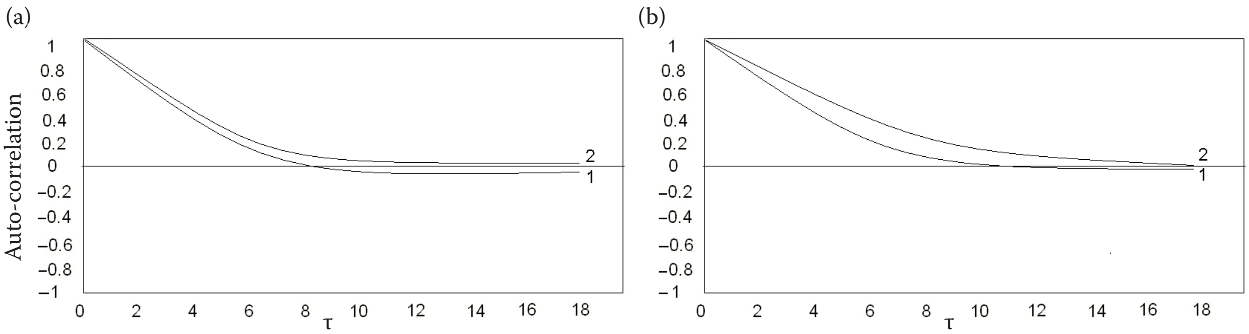

Fig. 7. Auto-correlation of spruce number of trees (1) and biomass (2) on PRP 1 (a) and PRP 2 (b) in warm-dry climate change scenarios

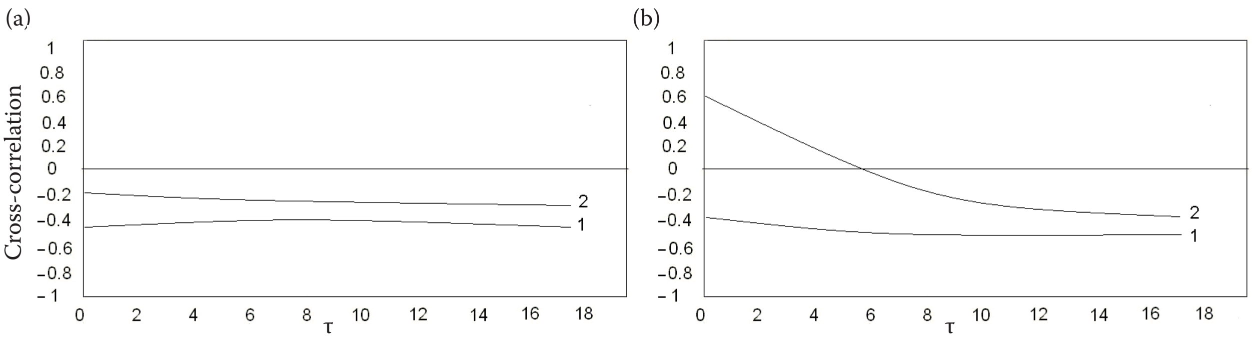

Fig. 8. Cross-correlation between the spruce and fir number of trees (1) and biomass (2) on PRP 1 (a) and PRP 2 (b) in warm-dry climate change scenarios

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tween spruce and fir will be changed from positive to negative for the number of trees that is more similar to PRP 2 situated at the lower altitude.

The relation between spruce biomass and all tree (stand community) biomass for PRP 1 in the warm-dry climate scenario will be similar to PRP 2 in the control. For the number of trees the cross-correlation transformed from strongly positive (up to $\tau = 12$ in the control) to moderately negative, similarly like for PRP 2 in this scenario (Fig. 8b).

DISCUSSION

The article presents the outlook for the application of FORKOME computer model to the prognosis of the impact of natural disturbances on spruce forests. The FORKOME model, in its latest version, includes a recently created and constantly developed block of forest drying up. As a result, it is possible to simulate potential changes caused by the drying up process, and thus to predict the impact of this disturbance agent on forest conditions and stand regeneration by conducting simulations on the issues concerned.

The sensitivity analysis, which was carried out, showed the existence of the internal memory of biomass and number of trees. These values mean that the individual states of biomass and number of trees parameters for development, achieved in the intervals of the τ_n time distances, are determined by the development states of these parameters, achieved in the past model time – corresponding to the intervals τ_{n-1}. Depending on the value of the correlation function, the determined correlation parameter is stronger or weaker.

The FORKOME model combines ecological and empirical relations (Brzeziecki 1999; Bugmann 2001). On the basis of the results generated by the FORKOME model, the hypothesis that in the period of 10–12 years spruce may lose the dominant species position within the analysed area regarding the number of trees as well as their biomass seems reasonable. That indirectly confirms that spruce in the Transcarpathian region is exposed to damage. Obtained results also suggested that even the smallest climate changes, especially in air temperature and precipitation, can cause a decrease in spruce biomass and number of trees. It is consistent with data presented in literature. For example, Debrynuk (2011) reported that in connection with further climate changes, the consequence of which is a gradual increase in the average annual air temperature and a decrease in precipitation, the drying up of spruce forests in the region will continue. Beech and fir-beech forest types are intensified by natural regeneration of beech forests, the best conditions for growth will be for sycamore maple and fir. Similar results were presented in our FORKOME model simulations. It means that we can introduce into existing forest stands the species that can provide the highest stability and productivity of phytocoenosis, as proposed by Debrynuk (2011).

Unfortunately, in the countries of Western Europe there were only small remnants of natural forests. In this regard, virgin forests in the Ukrainian Carpathians and their research are extremely important for the close-to-nature forest management throughout Europe. One of the examples of such management and regeneration methods is our analysis based on FORKOME model simulation, conducted on data from virgin forests in the Ukrainian Carpathians. The area of damaged forests in the Ukrainian Carpathians has been constantly increasing. For that reason, computer simulation using the FORKOME model is very promising. The FORKOME model predicted decreases of spruce biomass and number of trees. This tendency emphasizes once again the relevance of introducing sustainable forest management methods that increase the sustainability of forests.

Currently, the decline of secondary spruce forests is very intensive in the Ukrainian Carpathians (Parpan et al. 2014). The main reasons are deterioration of spruce stand stability due to global warming, spruce planting in forest conditions not typical of spruce, environmental pollution, massive spread of spruce diseases and pests, as well as the spruce stand damage by windfalls and snow.

CONCLUSION

Modelling scenarios for the period of 100 years showed a sharp decline of spruce in biomass in the first decade. Especially sensitive to changing climatic conditions were spruce stands. Their share in biomass decreased in both scenarios in favour of fir, beech and sycamore maple, which were characterized by a much better adaptation to warmer and drier conditions for the next decades. The FORKOME model predicted that in control conditions the biomass of spruce trees decreased on PRP 1 and on PRP 2. The model predicted an increase of fir and beech biomass in

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100 years of simulation. Similar tendencies were noticed for the number of trees.

The FORKOME model predicted for both plots that the biomass of spruce trees decreased to zero in the warm-dry scenario. After reaching the minimum biomass, the model predicts that spruce will be at the minimum level (2.3 ± 0.6 t·ha^{-1}) in 100 years of simulation. The model predicted an increase in the tree number of fir (to 88 individuals) and beech (to 90 individuals) in 100 years and a decrease in spruce tree number (to 5–10 individuals) in the 100th year. The number of sugar maple individuals increased to 43 individuals on PRP 1 at the end of simulation and to 10 individuals on PRP 2. Results in the cold-wet scenario were a good way of observing the model performance and checking the warm-wet scenario results mentioned above.

The cross-correlations conducted in FORKOME model confirm the lack of a strong correlation between spruce and fir biomass. The strong cross-correlation on the level higher than 0.75 up to τ = 12 was noticed only between spruce and fir tree number on PRP 1.

In the warm-dry conditions the auto-correlation of spruce concerning the number of trees on PRP 1 was lower compared to the control scenario. On PRP 1 the number of trees and biomass correlations in the warm-dry scenario were similar to the autocorrelation for PRP 2. It means that in this warm-dry scenario the correlations on PRP 1 will be similar to the correlations on PRP 2 in the control.

Improvement of the FORKOME model provides grounds for arguing about possibilities and forecasts for the development of spruce stands.

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