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Status and development trends of Scots pine plantations outside the species areal in Bulgaria

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Abstract

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Our study attempted to find a spatial analogue of the anticipated climate change in present times by investigating the status and development trends of four half-century-old man-made Scots pine stands outside the species areal in Central and North-Eastern Bulgarian lowlands. Stand composition, competition intensity, stand stability, site quality, tree mortality and ecosystem fit according to nationally established standards, were evaluated and growth correlations with climatic variables were analysed. Two stands experiencing an ongoing dieback were distinguished, regardless of the good productivity potential of the trees (Stand 2) or the low competition pressure and good mechanical stability maintained (Stand 1). The other 2 plantations showed either no mortality (Stand 4) or mortality due to self-thinning (Stand 3), forming a relatively productive and dense pure Scots pine stand (Stand 4) or a mixed, highly productive stand with diverse composition and good structure and stability (Stand 3). Tree growth was positively affected by the summer and the annual precipitation amounts, while negative correlation was found with the summer heat moisture index. Our investigation revealed that pine growth still can be sustained even in a slightly humid climate, if a high productivity level and good stand structure are assured, that indicates the overall capability of the species to adapt. However, the Scots pine trees are not able to adapt to relatively dry environmental conditions, suitable for lowland thermophilic species such as oaks, where the stands collapse when the heat-moisture balance worsens.

Keywords

climate change, competition, ecosystem fit, heat-moisture balance, mortality, *Pinus sylvestris* L.

Introduction

Factors of the physical environment, which determine forest dynamics and are generally related to temperature and humidity limitations, but also include large-scale disturbances such as snowthrows, fires, flooding etc., have shown to change much faster in the 21st century than during the past several hundred years (Fontes et al., 2010). An increase in temperature of about 0.7 °C in the 20th century was suggested by the global data, and for Europe this increase was 0.95 °C (IPCC, 2007). In addition, according to the Shared Socioeconomic Pathways (SSPs) of the projected global changes (Riahi et al., 2017) the estimated climate warming until year 2100 lies within the range

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between 1 and 5.7 °C (IPCC, 2021). Allen et al. (2010, 2015) pointed out that one of the major potential effects of warming climate across terrestrial biomes is the increase in climate-driven tree mortality. Scots pine (*Pinus sylvestris* L.), which is a widespread tree species in the northern hemisphere, has the southernmost boundaries of its areal in Europe in the mountainous regions of the southern parts of the continent (e.g., in Bulgaria). The populations at the margins of the species' range (e.g., the Bulgarian Scots pine populations) usually show lower performance in fitness-related traits than core populations (Vizcaíno-Palomar et al., 2019) and therefore, under the expected climate change, these populations could be at a higher risk of maladaptation. Also, Tkach et al. (2020, 2024) reported that natural oak stands grown from seeds are more productive and more resistant to adverse environmental factors and climate change than plantations. While the natural Scots pine stands in Bulgaria occupy areas at altitudes between 800 and 2,000 m asl (Penev et al., 1969), in 2010 about 50% of the plantations of this species are found outside its natural range, at lower altitudes, growing under warmer and dryer climatic conditions (Popov et al., 2018). Raev and Rossnev (2003) reported that in Bulgaria 18.5% of the plantations below 800 m asl, primarily coniferous, died out during the 1982–1994 dry period. Vulnerability of pines to drought was explained with their evolutionarily inherent disadvantages at such adverse conditions, which are related to their wood anatomy and permanently kept foliage. Soil moisture and air humidity, which not only sustain the photosynthetic process, but also play a vital role for the health status of the trees are considered the factors limiting growth of the Scots pine, particularly in the lower altitudinal range (Popov et al., 2018; Aleksandrov and Tonchev, 2021).

Considering the above-mentioned specifics and the resilience-related issues of the Scots pine plantations the concept of the ecological compliance (Gordon et al.,1996) was adopted by Kostov (2014) and Aleksandrov and Tonchev (2021) to classify the pine plantations in Bulgaria according to their ecosystem fit and to subsequently develop adequate management guidelines (Kostov et al., 2023). The classification by Kostov (2014) was suggested as a two-dimensional chart with the estimate of soil richness and humidity according to Pogrebnyak' scale (Pogrebnyak, 1955) presented on the abscissa and the altitude, as an indirect characteristic of climate, placed on the ordinate, with the origin positioned at the optimum of the ecosystem fit. Four concentric zones numbered 1 to 4 outward of decreasing from the origin to the periphery ecosystem fit, are differentiated. In a study of the Scots pine plantations in south-western Bulgaria, Aleksandrov and Tonchev (2021) developed the classification further by quantifying the two principal factors: the soil complex, elaborated as composed of five soil characteristics and the relief complex, specified as a proxy of climate through the numerically presented aspect, slope, altitude, and landform. The authors applied the classification factors to derive analytically two groups of Scots pine plantations for the explored region: of good (group AB) and of poor (group C) ecosystem fit.

An extended investigation of the 1982–1994 dry period (Raev et al., 2003) referred to it as "A contemporary analogue for climate change" considering the presumed resemblance of its effect on the natural resources and the society. Monitoring of permanent sample plots (PSP) in Scots pine plantations outside the species natural range at lower altitudes, would probably suggest a spatial climate change-resembling analogue. For this purpose, four such plots were established in 2023–2025 in around half-century-old Scots pine plantations in Central and North-Eastern Bulgarian lowlands. Our study aimed to assess the status of these man-made Scots pine stands outside the species areal in Bulgaria in terms of competition intensity, tree species diversity, stand stability, site quality and ecosystem fit. Furthermore, it intended to analyse the development trends observed regarding tree mortality and tree diameter growth as related to climate. Finally, based on all parameter assessments and their comparison between the stands, our study tried to derive conclusions about the ability of the species to adapt to climate change.

Materials and methods

The investigated forest stands have been established in

Table 1. Description of the experimental sites

PSP	Latitude	Longitude	Altitude (m)	Aspect	Slope (degrees)
PSP 1 – Bolyarka	43°09'28.1"N	25°06'19.5"E	486	S	6
PSP 2 – Dunav	43°50'13.3"N	26°05'35.3"E	155	S	0
PSP 3 – Razgrad	43°27'8.9"N	26°31'13.6"E	450	SE	4
PSP 4 – Maglizh	42°39'38.1"N	25°40'57.0"E	620	SW	10

PSP	Site type*	Plot area (m^2)	RSG	Temperature**	Precipitation**
PSP 1 – Bolyarka	MTY-1 C-2	447.53	Rendzic Leptosols	10.3 (1.3)	639.8 (109.2)
PSP 2 – Dunav	M-I-2 D-1	700	Chernozems	11.3 (1.1)	601.2 (108.8)
PSP 3 – Razgrad	M-I-2 D-1	1496.35	Phaeozems	10.1 (1.2)	614.7 (110.7)
PSP 4 – Maglizh	T-I-3 C-2,1	1033.58	Cambisols	9.9 (1.3)	675.5 (112.9)

PSP – permanent sample plot; RSG – Reference soil group according to the World Reference Base for Soil Resources (WRB, 2014).
*Site types are determined according to Classification scheme of the forest site types in Bulgaria (Executive Forest Agency, 2011).
**Mean value is presented, with the standard deviation in parentheses.

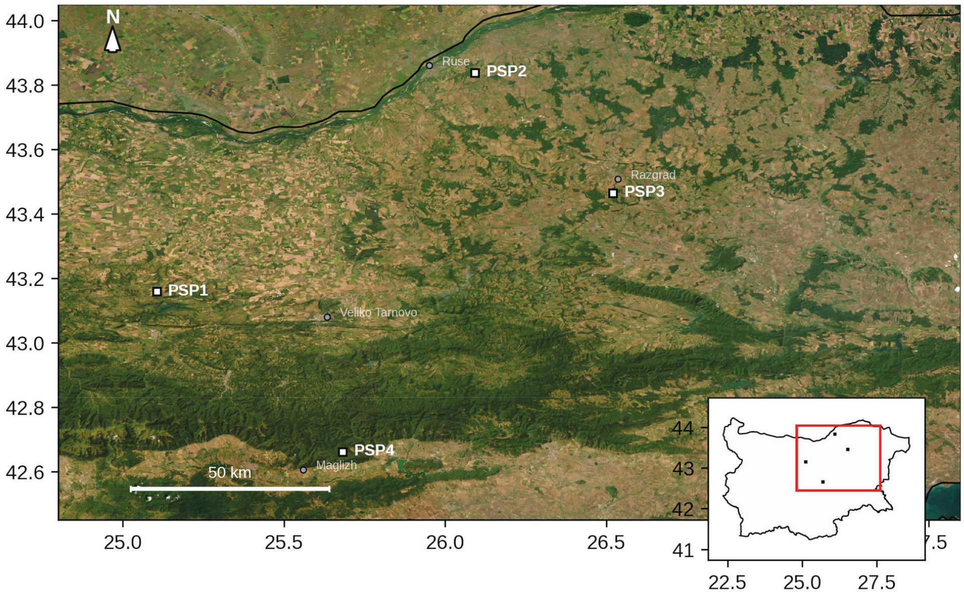

Fig. 1. Locations of the Permanent Sample Plots (PSP).

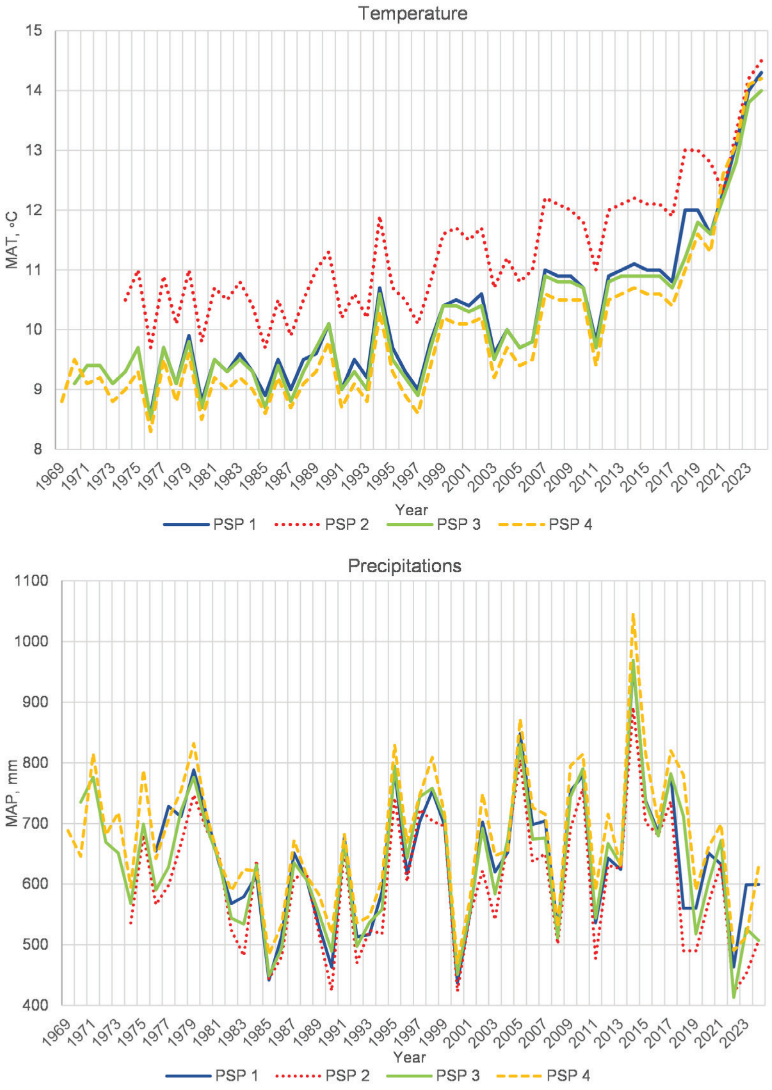

Fig. 2. Long-term climatic conditions at the experimental sites. MAT – mean annual temperature (degrees); MAP – annual precipitation amount (mm).

the 70-s as pure (PSP1, PSP2, PSP4) or partially mixed (20%) with Black pine (*P. nigra* Arnold) (PSP3) Scots pine plantations. They grow on sites of southern aspects, on flat or sloping terrains at altitudes below 650 m asl, on medium-rich or rich, dry or fresh soils and are located on the territory of four State Forestry or Hunting Units (SFU Bolyarka – Veliko Tarnovo, SHU Dunav – Ruse, SFU Razgrad and SFU Maglizh) in Central and North-Eastern Bulgaria (Table 1, Fig. 1). Mean annual temperatures and precipitation amounts at the stand locations (Marchi et al., 2020; Visual Crossing Corporation, 2025) are shown in Table 1 and the trends in these variables since plantation establishment – in Fig. 2.

Permanent sample plots of different shapes (3 rectangular and 1 circular) and sizes (from 447.53 to 1,496.35 m^2) were installed in 2023 and 2025 in consideration of the site and stand specificities (Table 1). All trees in the plots were numerated at breast height (1.3 m from the base) using plastic plates with unique serial numbers. In each sample plot, the number of trees per species was counted and the status of every tree (dead or alive) was determined, noting any kind of damage as well from biotic or abiotic factors. For PSP1 this was done twice: at the time of plot establishment in 2023 and 2 years later. Measurements of two perpendicular to each other stem diameters were taken with 0.1cm precision at the plate height using a calliper and were averaged to determine the breast-height diameter of every tree in the plot. Heights of 20% of the trees in each diameter class (by 1 cm) were measured with Haglöf IV hypsometer. In 3 of the 4 plots (except for PSP4 Maglizh that was in a private forest), wood cores were extracted at the stem bases of five trees of above average size and without manifestation of butt swell with an increment borer (Husch et al., 2003). The increment cores were processed at the laboratory according to the established protocol (Tsvetanov et al., 2024), scanned with Epson Expression 12000XL scanner and then the tree rings were counted, and their widths were measured on the scanned images using CDendro+CooRecorder software Version 9.8.1 (Larsson, 2022).

Data collection took place outside the growing season, during the autumn-winter growth cessation period. Therefore, tree species diversity and evenness in each plot were evaluated by employing Shannon diversity index H and standardized diversity index E (Pretzsch, 2009) only for the canopy-forming woody species and were used to assess stand composition. Between-tree competition was determined according to the distance-independent competition index BALMOD by Schröder and Von Gadow (1999), which is based on the basal area percentile of the tree and the relative spacing of the stand that allows comparison of the competition levels of different stands:

$$BALMOD_{ij} = \frac{1-p_j}{RS_i} \quad (1)$$

$$RS_i = \frac{\sqrt{10000/N_i}}{H_i}\ , \quad (2)$$

where p_j is the basal area percentile of tree j, RS_i is the relative spacing of stand i, N_i is the number of trees per hectare of stand i and H_i is its dominant stand height.

Further, more detailed examination was carried out of the upper stand layer formed by the planted dominant tree species Scots pine. The average breast height tree diameter and tree height in the plots were calculated as quadratic mean diameter and basal area-weighted (Lorey's) mean height, respectively and mean stand stability was estimated according to the mean height to mean diameter ratio (HDR). Dominant stand height, defined as the average height of the 100 thickest trees per hectare, was calculated from the measured heights of the dominant trees in the plots. Site index was assessed from the growth and yield tables by Krastanov et al. (1983a) as well as from the site index model of Stankova et al. (2024). The diameter distributions of the subsets of dead and alive Scots pine trees in each plot were analysed graphically, and the dead wood volume was estimated according to the volume and assortment tables of Krastanov et al. (1983b). Stand-level estimates of tree density (trees ha^{-1}) and dead volume (m^3 ha^{-1}) were obtained from the respective plot-level values of these variables. Precise evaluation of plantation age was the primary purpose of the increment core collection. However, we adapted the methodological approach employed in dendrochronology, to take advantage of the collected samples and to investigate possible correlations between basal diameter growth and annual and seasonal climatic variables (precipitation amounts, average temperatures and heat: moisture indices). By summation of the annual basal diameter increments we first calculated the basal diameter values during the entire life span of the trees. Then, we examined 10 principal growth models (Stankova et al., 2024) in their integral equation form to model the individual tree diameter growth by stands. The most adequate in each case formulation was chosen as the one of the smallest errors, as indicated by the bias, the mean of the absolute errors and the mean squared error, and the biggest prediction potential, indicated by the highest value of the adjusted coefficient of determination. The selected functions were then examined in dynamic – algebraic difference (ADA) and generalized algebraic difference (GADA) equation forms (Stankova et al., 2024) and within the mixed-effects modelling framework assuming tree-specific model parameters. Their adequacy in terms of residual diagnostics and model bias was assessed, and serial correlation structure was added to account for the residual autocorrelation (Pinheiro and Bates, 2000), which is intrinsic to the time series data. The adequate growth model of the highest predictability was chosen for each stand according to Akaike weights (Wagenmakers and Farrell, 2004; Sileshi, 2014). The best growth models were then used to predict the individual tree diameters, to calculate the predicted increment values and to standardise the individual increment series. The possible correlations of the standardised increment series averaged per plot with annual and seasonal climatic variables (Table 5) were investigated afterwards. The European database ClimateEU (Marchi et al., 2020) and Global Weather Data and API for Every Application database (Visual Crossing Corporation, 2025) were used to extract the historical records of climatic variables at the plot locations until 2020 and from

2021 to 2024, respectively. The variables of higher correlation with growth were further examined as predictors in a multiple linear regression model by stepwise backward selection. Collinearity of the regression models was assessed and controlled by the condition number (<30) and the variance inflation factor (<10) and when the thresholds were exceeded, reduced-form model combinations were tested and proposed instead, taking into account the correlation matrix of the predictor variables.

Finally, assessment of the ecosystem fit of the investigated Scots pine plantations according to the classifications by Kostov (2014) and Aleksandrov and Tonchev (2021) was carried out.

Results and discussion

The forest stands represented in PSP1 and PSP4 were nearly pure Scots pine plantations of a simple 1-floor canopy, while those in PSP2 and PSP3 were characterised by 2-floor canopies with the upper canopy layer consisting of Scots pine and Black pine trees and the lower floor composed of broadleaf tree species. The latest two stands exhibited, respectively, higher level of tree species diversity, as indicated by Shannon's index H (Table 2). The forest stand in PSP3 was composed of 4 tree species (*Pinus sylvestris* L., *Pinus nigra* L., *Acer pseudoplatanus* L., *Tilia argentea* Desf.), while 7 tree species were counted in PSP2 (*Pinus sylvestris* L., *Pinus nigra* L., *Tilia argentea* Desf., *Tilia cordata* Mill., *Fraxinus oxycarpa* Willd., *Padus mahaleb* Borkh., *Robinia pseudoacacia* L.). However, each of the species in PSP3 participated by more than 10% in the stand composition that yielded the highest Diversity and Equitability Indices of all plots, while the limes in the second floor of PSP2 accounted for more than 80% of the trees, leaving the other species underrepresented (Table 2). PSP4 characterised a pure Scots pine plantation, while single Black pine (*Pinus nigra* L.) and Silver fir (*Abies alba* L.) trees were found in PSP1.

Relative spacing (RS), that was estimated from all live trees in the plots, suggested that the investigated stands should be defined as "dense" (PSP1, 0.16 < RS < 0.22) and "very dense" (PSP2, PSP3, PSP4, RS < 0.16) (Schröder and Von Gadow, 1999). This was reflected in the between-tree competition intensity, which average rates indicated severe (PSP2) and moderate (PSP3, PSP4) competition in most of the cases (Table 2, Fig. 3). Clearly, the trees in PSP2 are exposed to the strongest competition pressure due to abundant regeneration of broadleaves in the second floor, while those in PSP1 that are developing at a wider relative spacing are the most relieved from competition for resources. The trees in the pure Scots pine plantation of PSP4, which has the second smallest relative spacing, seem to experience stronger competition pressure than those in the mixed stand in PSP3 (Fig. 3).

HDR is usually defined as one of the most important criteria for evaluation of stand stability (the lower the HDR, the higher the stability) to wind and snow damages

Table 2. Composition and competition characteristics of the forest stands

PSP	Shannon Diversity Index H	Shannon Equitability Index E	RS	BALMOD*
PSP 1 – Bolyarka (2023)	0.287	0.262	0.184	2.94 (1.10)
PSP 2 – Dunav	0.959	0.493	0.104	8.95 (1.41)
PSP 3 – Razgrad	1.194	0.861	0.141	4.20 (1.51)
PSP 4 – Maglizh	0		0.121	4.72 (1.15)

PSP – permanent sample plot; RS – Relative spacing; BALMOD – competition index.
*Mean plot value of the competition index is presented, with the standard deviation in parentheses.

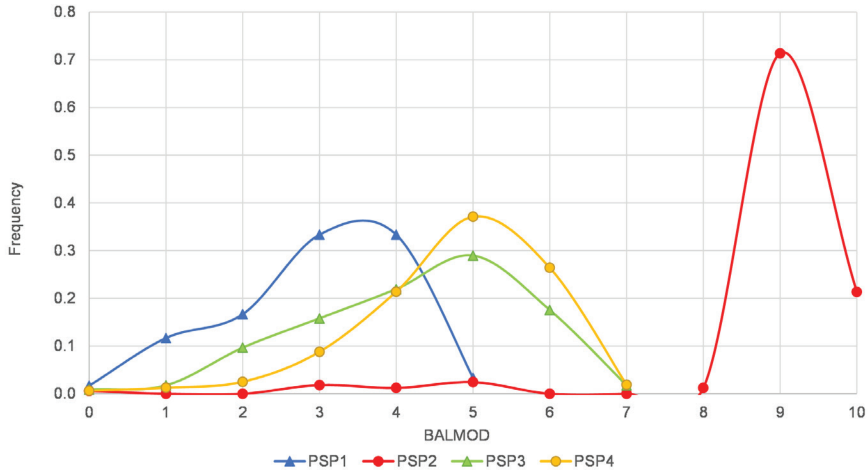

Fig. 3. Competition rates by sample plots.

on tree stems and crowns (Nykänen et al., 1997; Peltola et al., 1999; Petty and Worrell, 1981; Zhu et al., 2006). The highest values of HDR are observed in PSP4, with the smallest proportion of trees with favourable estimates of this coefficient (Table 3, Fig. 4). However, no considerable signs of mechanical damages on stems were observed in PSP4, with only presence of twist rust (*Melampsora pinitorqua* Rostr.). The tendency of HDR according to diameter of PSP1 is similar to that of PSP4 (Fig. 4), but with smaller overall HDR values indicating stems of higher stability, which is probably related to the bigger relative spacing and weaker competition in this stand (Table 2, Fig. 3). The trends of HDR according to diameter of PSP2 and PSP3, on the other hand, are also alike and indicate that the Scots pine trees of the upper stand layer in these stands possess good mechanical stability, of comparable values for the different diameter classes (Fig. 4).

Assuming that tree height is an effective integrator of the key biological determinants of growth (Weiskittel et al., 2011), the expected stand height at a certain reference age (site index), has become the most popular indirect measure of site productivity (Skovsgaard and Vanclay,

Table 3. Characteristics of the planted Scots pine stands

PSP	Initial density (trees ha^{-1})	Current density (trees ha^{-1})	QMD (cm)	Hm (m)	Age (years)	H0 (m)	HDR	Dead volume (m^3 ha^{-1})
PSP 1 – Bolyarka (2023)	5,000	1,877	16.38	14.01	47	14.85	0.86	99.2884 (2023) 128.4146 (2025)
PSP 2 – Dunav	5,000	686	24.80	18.38	50	19.91	0.74	271.7857
PSP 3 – Razgrad	4,444	521	29.75	25.08	54	25.75	0.90	82.5912
PSP 4 – Maglizh	5,000	1,577	19.43	20.28	55	21.05	1.04	6.1098
	Site quality			EF by Kostov (2014)		EF by Aleksandrov and Tonchev (2021)		
	Site index by Krastanov et al. (1983)	Site index by Stankova et al. (2024)*		Zone	Quadrant	Group	Quadrant	
PSP 1 – Bolyark (2023)	IV	16 (c_0 = 6.804)		3/4	2	C	3	
PSP 2 – Dunav	II	20 (c_0 = 6.697)		4	2	C	3	
PSP 3 – Razgrad	Ia	25 (c_0 = 6.757)		3	2	C	4	
PSP 4 – Maglizh	II	20 (c_0 = 6.976)		3	2	C	4	

PSP – permanent sample plot; QMD – quadratic mean diameter; Hm – mean height; H0 – dominant height; HDR – mean height to mean diameter ratio; EF – Ecosystem fit.
*Site index estimated as the dominant stand height H0 (m) at 50 years of age is presented, with the stand specific parameter c_0, as a function of site-specific geocentric predictors, in parentheses.

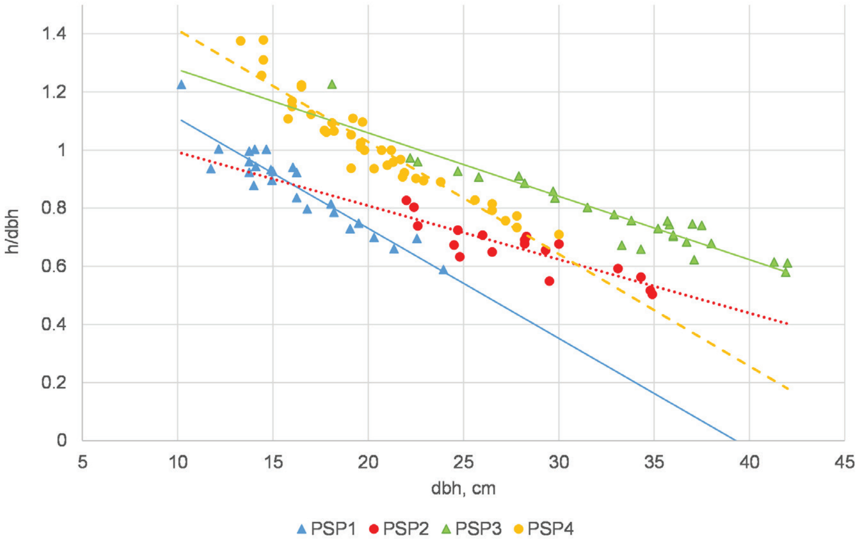

Fig. 4. Change in stand stability with the breast height tree diameter by plots.

2008). The estimates of both the relative site index according to average stand height following Krastanov et al. (1983a) and the absolute site index according to dominant stand height following Stankova et al. (2024), revealed that the Scots pine plantation in PSP1 is the least productive, while that in PSP3 possesses the highest growth potential, with PSP2 and PSP4 showing intermediate and similar productivity levels (Table 3). The latest result contrasts the observed survival rates of the Scots pine trees in the same plots, where the pine plantation of PSP2 has practically perished while that of PSP4 flourishes (Fig. 5). This observation confirms once again that the site index is not a relevant indicator of the ecosystem fit of the man-made pine stands (Popov et al., 2018). Stankova et al. (2024) attempted to reflect the influence of the environmental factors on growth through the specific parameter of the site index equation. When applied in parallel to PSP2 and PSP4, the climate-sensitive site index model showed lower value of the site-specific parameter c_0 for PSP2 than for PSP4 (Table 3), implying more favourable environmental conditions for pine growth in PSP4. This result generally suggests a possible deviation between the height growth trajectories of both stands, with slower height growth of later culmination and lower asymptote for the lower value of c_0 (PSP2), assuming that both stands have retained vitality.

While the overall mean temperatures and precipitation amounts are similar or do not vary much between the sites (Table 1), their dynamics during the last more than 50 years shows distinctly more adverse temperature-humidity regime at the PSP2 site location, more favourable

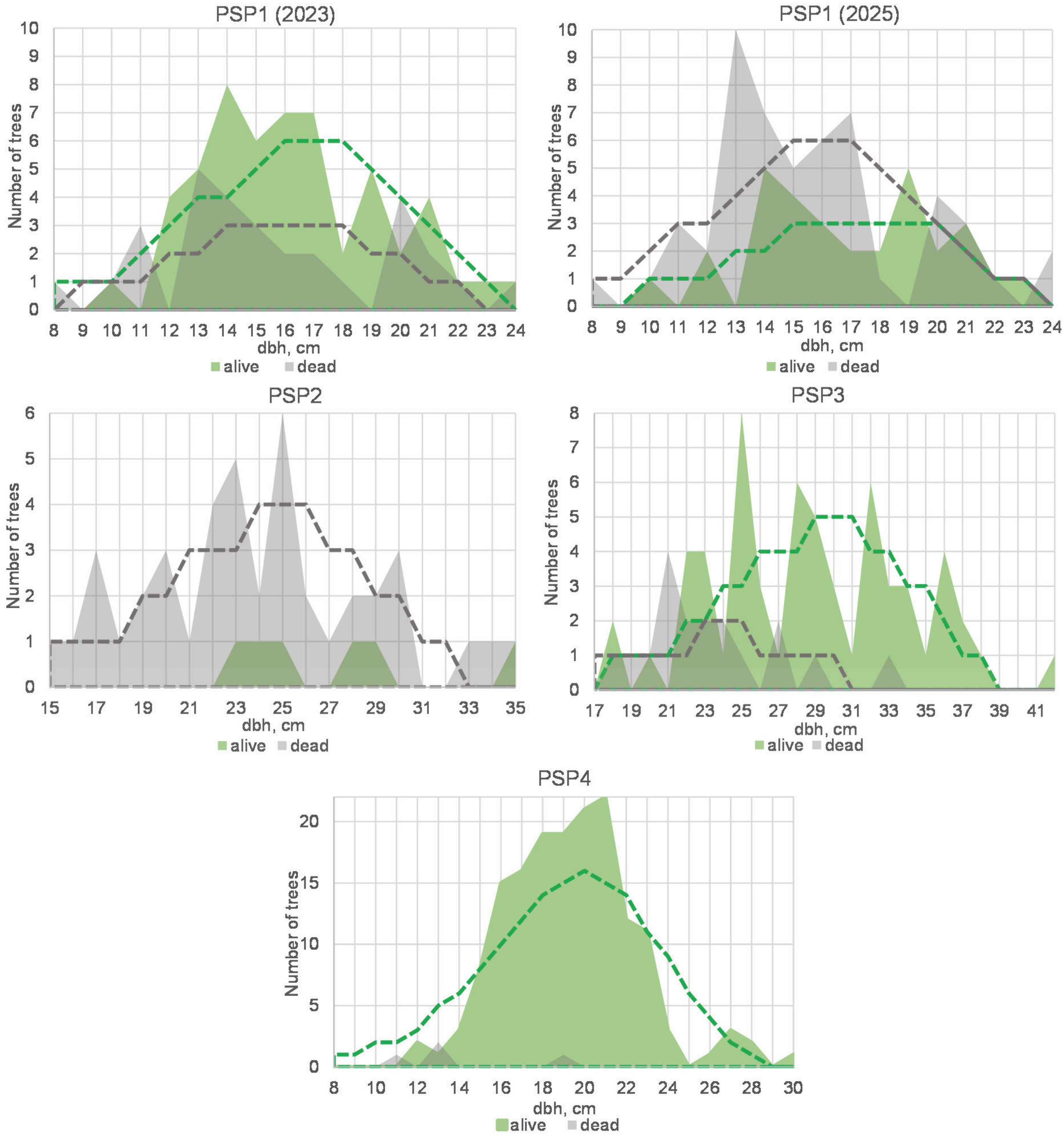

Fig. 5. Tree diameter distributions by subsets of dead and alive trees.

for pine growth at the PSP4 site location, with PSP1 and PSP3 being at similar, intermediate climatic conditions. Continuous worsening trend of decreasing precipitations and increasing temperatures is manifested after 2017 (Fig. 2), suggesting that this ongoing period of harsh conditions is a leading stress factor that affects the current status of the examined plantations. According to the classification of the forest vulnerability zones with respect to the index of De Martonne (Raev et al., 2015), the explored Scots pine plantations are categorized in C – medium (PSP1, PSP3, PSP4) and B – highly (PSP2) vulnerable to drought zones with slightly humid and moderately dry climate, respectively. The study by Raev et al. (2015) predicted that according to the optimistic Representative Concentration Pathway (RSP) RSP2.6 the Scots pine stands in Bulgaria in year 2050 will fall predominantly into the medium vulnerable forest zone C and according to the pessimistic RSP8.5 – into the highly vulnerable forest zone B.

Mortality is considered one of the least understood processes of stand dynamics (Hamilton, 1986) as it is driven by a variety of predisposing, inciting and contributing stress factors resulting in a range of tree survival affecting causes (Bravo-Oviedo et al., 2006). To simplify the approach to such a complex phenomenon, mortality has been commonly considered either as regular, when caused by competition for resources, or as irregular, when caused by ecological and catastrophic events, such as windthrows or fires (Monserud, 1976). Gendreau-Berthiaume et al. (2016) suggest that information on the size structure of living and dead trees can provide valuable insight into the processes driving mortality. The competition-induced mortality would primarily affect the small-sized trees of inferior vigour to grow and compete. On the other hand, if mortality is distributed equally across all size classes or is proportionally more important in larger size classes, this would indicate that mortality was not from self-thinning (Gendreau-Berthiaume et al., 2016). The result of the consecutive inventories of PSP1 over 2-year period of growth implies that we have been observing the stand in an ongoing dieback period. The mortality of trees from all diameter classes (Fig. 5), considering also the relatively low competition pressure assessed for this stand (Table 2), leads to the conclusion that the adverse heat-moisture balance (Fig. 2) observed recently could be the reason. The climatic stress factor has been even more detrimental for the stand of PSP2 (Fig. 2), the competition with the ingrowth of the autochthonous broadleaves complicating the situation, with an overall result of more than 90% dead Scots pine trees (Fig. 5) and over 270 m^3 ha^{-1} dead volume (Table 3). The small size of the dead trees in PSP3 is illustrative for competition-induced mortality (Fig. 5), while the neglectful number of dead trees in PSP4, given the relatively high competition pressure, estimated for this stand (Table 2) infers that the particular environmental conditions of its site suffice the tree requirements for resources.

Tree basal diameter growth of PSP1 and PSP2 was best described by Johnson- Schumacher (Grosenbaugh, 1965) growth model, while that of PSP3 – by the model of Hossfeld (cited in Elfving and Kiviste, 1997). The relevant dynamic equations described polymorphic individual growth trajectories presented by algebraic difference (PSP1, PSP3) and generalised algebraic difference (PSP2) equation forms (Fig. 6, Table 4). The sampled trees in PSP2 revealed stunted growth between 15 and 25 years of age that has been released by a documented thinning in 1998 (Fig. 6). Fitting of a segmented growth curve to these data was attempted to better describe the observed trajectories, but an improvement was not achieved. Either (PSP2, PSP3) or both (PSP1) regression parameters were fitted as tree specific and Moving Average correlation structures were included to model residual autocorrelation (Table 4). Predicted annual radial increments were calculated from the fitted growth models and for each plot

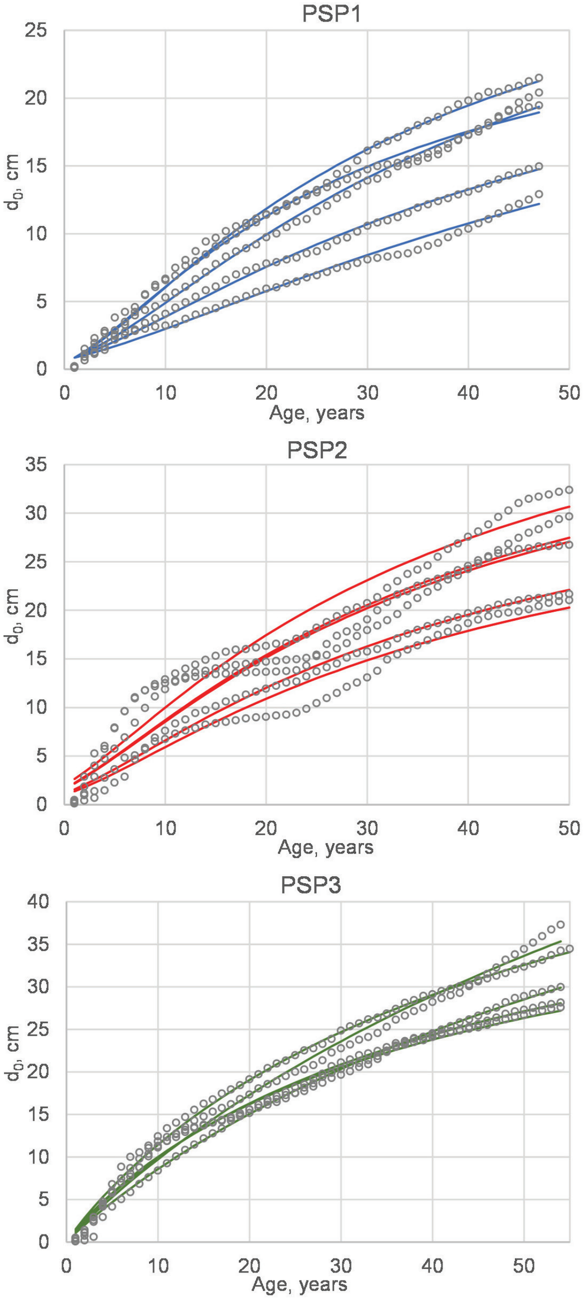

Fig. 6. Basal diameter (d0) growth of individual trees, approximated by dynamic growth equations.

Table 4. Diameter growth models of individual trees

PSP	Model	ME	Fixed effects*	Random effects	Correlation structure
PSP 1 – Bolyarka	Integral equation form: $D = aexp(-\frac{b}{t+c})$ (Johnson-Schumacher and Grosenbaugh, 1965) Dynamic equation form: $D_2 = a\left(\frac{D_1}{a}\right)^{(t_1+c)/(t_2+c)}$	0.994	a = 35.306 (2.603) c = 10.469 (2.064)	sd(a) = 4.293 sd(c) = 3.653 sd(res) = 0.467	MA(7)
PSP 2 – Dunav	Integral equation form: $D = aexp(-\frac{b}{t+c})$ (Johnson-Schumacher and Grosenbaugh, 1965) Dynamic equation form: $a = exp(X),\ b = c_0/X$ $X = 0.5\left(ln(D_1) + \sqrt{(ln(D_1))^2 + 4c_0/(t_1 + c)}\right)$ $D_2 = exp\left(X - c_0/(X(t_2 + c))\right)$	0.952	c = 10.451 (2.553) c_0 = 138.58 (27.414)	sd(c) = 0.0002 sd(res) = 1.476	MA(10)
PSP 3 – Razgrad	Integral equation form: $D = a/(1 + bt^{-c})$ (Hossfeld, cited in Elfving and Kiviste, 1997) Dynamic equation form: $D_2 = \frac{at_2^c}{t_2^c + t_1^c\left(\frac{a}{D_1} - 1\right)}$	0.993	a = 71.091 (12.175) c = 0.946 (0.037)	sd(a) = 21.863 sd(res) = 0.612	MA (4)

PSP – permanent sample plot; ME – model efficiency; MA – Moving average correlation model; sd – standard deviation; a, b, c, c_0 – model parameters; t, D – tree age (years) and basal tree diameter (cm), respectively, in the integral equation forms; D_1 – current (or predictor) basal tree diameter (cm) at time t_1 expressed by the tree age in years; D_2 – future (or predicted) basal tree diameter (cm) at time t_2 expressed by the tree age in years.
*Standard errors in parentheses.

the correlations between the series of ratios to the actual increment values of the trees were assessed. The standardized increment series of one tree in each plot showed lower correlation with the rest of the trees and, after its exclusion, values of 0.82 (PSP1, PSP2) and 0.84 (PSP3) of the Expressed Population Signal (EPS) were estimated. Although an EPS value of 0.85 is the generally accepted threshold for the reliability of a chronology (e. g., Tsvetanov et al., 2024), we assumed that the threshold of 0.8 would be a reasonable compromise to continue our study, moreover, it was achieved by only 4 trees per plot. We then examined the presence of correlations between the standardized basal radial increments, averaged per year per plot (I_t), and 17 seasonal and annual climatic variables (Table 5). Relatively low, but significant correlations were found in most of the cases, distinguishing the positive effect of the summer (corr (MSP) = corr (PPT_sm) = 0.34) and annual (corr (MAP) = 0.27, corr (MAP_p) = 0.25) precipitation amounts and the negative relation to the summer heat: moisture index (corr (SHM) = –0.25). Koulelis et al. (2025) also derived the crucial role of water availability in determining annual tree growth of Greek fir (*Abies cephalonica* Loudon), based on the high correlation to the Standardized Precipitation Index that they found. The weakness of the climatic signal in our study is probably due to lower sensitivity of the basal diameter growth and unexplored influential climatic predictors e. g., related to heat and moisture extremes. The climatic variables that had a correlation exceeding ±0.2 were tested as predictors in a multiple regression model. The final selection suggested that the most impactful combination of factors includes the precipitations of the preceding year and during the summer season (June–August), the average annual temperature and the summer heat: moisture index (Table 5). Our result is in line with the notion of Dimitrov (2025), who selected the growing degree days (as alternative to mean annual temperature) and the rainfall in August (similar to the summer precipitation amount) for modelling the potential distribution of Scots pine in Bulgaria. Our result agrees also with the finding by Panayotov et al. (2023) who modelled the ecological niches of the main tree species in Bulgaria and reported that the distribution of Scots pine is affected mainly by the temperature, the summer precipitations and the soil conditions.

Both ecosystem fit classifications, by Kostov (2014) and Aleksandrov and Tonchev (2021), define the Scots pine plantations of PSP1 (Zone 3/4, Group C + Quadrant 3) and especially that of PSP2 (Zone 4, Group C + Quadrant 3) as forest stands of a complete lack of ecosystem fit to the site conditions (Table 3). The pine plantations of this category are described as gradually vanishing, of poor

Table 5. Relationships between radial increment and climatic variables: linear correlation and multiple regression analyses

Climatic variable	MAT	MWMT	AHM	MAT_p	Tave_wt	Tave_sp	Tave_sm	Tave_at_p	DeM
Correlation coefficient	0.21	0.05	–0.18	0.20	0.16	0.22	0.10	0.19	0.20
Level of significance*	P < 0.001	P = 0.210	P < 0.001	P < 0.001	P < 0.001	P < 0.001	P = 0.021	P < 0.001	P < 0.001
Climatic variable	MAP	MSP	SHM	MAP_p	PPT_wt	PPT_ sp	PPT_sm	PPT_at_p	
Correlation coefficient	0.27	0.34	–0.25	0.25	0.03	0.18	0.34	0.17	
Level of significance	P < 0.001	P < 0.001	P < 0.001	P < 0.001	0.437	P < 0.001	P < 0.001	P < 0.001	
Regression model: $I_t \sim 1 + SHM + MAT + MAP\_p + PPT\_sm$									
Adj. R^2	*F*	Level of significance		Independent variables					
0.242	47.49	P < 0.001		Intercept	SHM	MAT	MAP_p	PPT_sm	
				–0.893 (0.223)	–0.005 (0.001)	0.140 (0.018)	0.001 (0.0002)	0.002 (0.0005)	

Adj. R^2 – adjusted coefficient of determination; *F*-test – Fisher's criterion; *P* (probability) – parameter of statistical significance; I_t – standardized basal radial increments, averaged per year per plot; MAT – mean annual temperature (in degrees); MAP – annual precipitation amount (mm); MWMT – mean temperature of the hottest month (degrees); MSP – mean summer (May–Sept.) precipitation (mm); AHM – annual heat: moisture index; SHM – summer heat: moisture index; MAT_p – mean annual temperature of the previous year (degrees); MAP_p – annual perception amount of the previous year (mm); Tave_wt – mean temperature of the winter months (Dec. – Feb.) (in degrees); Tave_sp–- mean temperature of the spring months (March–May) (in degrees); Tave_sm – mean temperature of the summer months (June–Aug.), (in degrees); Tave_at_p – mean temperature of the autumn months (Sept.–Nov.) of the previous year (degrees); PPT_wt – precipitation amount of the winter months (mm); PPT_sp – precipitation amount of the spring months (mm); PPT_sm – precipitation amount of the summer months (mm); PPT_at_p – precipitation amount of the autumn months of the previous year (mm); DeM – index of De Martonne.

health condition, without natural regeneration of pines, but broadleaves that finally replace the Scots pine (Kostov et al., 2023). Our data for PSP1 and PSP2 completely agree with this description, with stand decline obviously speeded up (Fig. 5) by the worsen climatic conditions during the last decade (Fig. 2) that weaken tree resistance to abiotic and biotic stress factors (Allen et al., 2010) such as, e. g. defoliation-causing biotic pests, which decrease tree growth and vitality (Georgieva et al., 2024). A resemblance can be found with the anticipated loss of pine growth-supporting site conditions under climate change at the cost of thermophilic species expansion northward and upward as suggested in studies by e.g., Thurm et al. (2018) and Panayotov et al. (2023). As Kostov (2014) noted, the plantations of the lack-of-fit category were usually established for special purposes, as green areas (e. g., PSP2) and for erosion control (e.g., PSP1) and therefore needed special care. Although the stand of PSP1 revealed poor productivity, it has been regularly thinned that assured good stand stability and low competition rate (Tables 2 and 3). The plantation of PSP2, on the other hand, has been developing in the most adverse climatic conditions (Fig. 2), has experienced stress still at an early age and the thinning conducted at 24 years of age has released the tree growth of the otherwise good productivity stand (Fig. 6, Table 3). Nevertheless, both stands have passed height growth culmination age long ago – 27 years for PSP2 and 30 years for PSP1, according to the site index model by Stankova et al. (2024), which was suggested as the best rotation age for the pine plantations of this category (Kostov, 2014).

The Scots pine plantations of PSP3 (Zone 3, Group C + Quadrant 4) and PSP4 (Zone 3, Group C + Quadrant 4) were classified by Kostov (2014) and Aleksandrov and Tonchev (2021) as forest stands of weak (insufficient) ecosystem fit that require particular care for improvement of their stability against wind and snow damages and protection against pests. Our results suggest that this advice is especially relevant to the pure Scots pine plantation (PSP4) that is developing at the most favourable climatic and site conditions (Table 1, Fig. 2), but manifested insufficient stability, moderate competition pressure (Tables 2 and 3) and showed signs of pest infestation (*Melampsora pinitorqua* Rostr.). The Scots pine plantation of PSP3, on the other hand, is a highly productive and a well-managed stand of good health status that has the potential to achieve more advanced rotation age. Our evaluation of its composition (tree diversity and evenness) and between-tree competition (Table 2, Fig. 3) disagree with the conclusion by Kostov (2014) that the Scots pine stands of Zone 3, Quadrant 2 (Kostov, 2014) suffer severe competition from the broadleaf species and cannot form 2-floor stands with them, which better characterizes PSP2 (Zone 4, Quadrant 2) of our study. In the study by Pretzsch et al. (2023), which derived three large growth trend regions for Scots pine in Europe, the pine plantations of PSP3 and PSP4 can be recognized as the stand type growing in class 1 areas, of positive but weaker growth trend, where other factors than climate seem to be the prevalent driving forces.

Conclusions

Our study attempted to find a spatial analogue of the anticipated climate change in present times by investigating the status and development of man-made Scots pine stands outside the species areal at low altitudes. The results showed that pine growth still can be sustained even in a remote from the mountainous region, slightly humid climatic environment, that indicates the overall capability of the species to adapt, if a high productivity level and good stand structure are assured by adequate selection and silvicultural measures. Our investigation confirmed, however, that the Scots pine trees are not able to adapt to a certain range of more suitable for lowland thermophilic species such as oaks, relatively dry environmental conditions, where the stands collapse when the heat-moisture balance worsens, regardless of the good productivity potential of the trees or the low competition pressure and good mechanical stability maintained.

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