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Ecosystem fit of Scots pine (*Pinus sylvestris* L.) plantations in south-western Bulgaria

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Abstract

A classification according to the level of ecosystem fit for plantations of Scots pine in south-western Bulgaria is proposed in this study. For this purpose, two indices which characterize the relief and soil conditions are used. The assessment of climatic conditions is made using the De Martonne index. The plantations are classified into four groups and two subgroups. The predominant part (55.8%) of the studied plantations grows in highly vulnerable to drought zone, while 35.5% are in the absence of ecosystem fit. This way of classification of the Scots pine plantations will allow to apply differentiated management regimes. In the present conditions of climate change, this classification can be used in estimation of the appropriate habitats for the afforestation by establishing Scots pine plantations in the future.

Keywords: adaptive management, climate change, aridity index, forest stands classification

Introduction

Forest ecosystems in Europe have been strongly influenced by climate change and other global changes (Shaver et al. 2000, Blennow and Sallnäs 2002, Askeev et al. 2005, Kellomäki and Leinonen 2005, Maracchi et al. 2005, IPCC 2007). Climate change is shifting the world's climatic zones, which affects the conditions in which tree species grow. Warmer and drier conditions will lead to more frequent and longer droughts, as well as an increased risk of fire (IPCC 2007).

Scots pine (*Pinus sylvestris* L.) is the most common coniferous species in Bulgaria. Scots pine forests cover an area of 560,085.8 ha, which comprised near 50% of all coniferous forest area and about 15% of the entire forest area in Bulgaria (Dakov 1979, EFA 2015).

Coniferous plantations in Bulgaria were established in the second half of the 20th century and resulted from the policy for increasing the forested area of the country to prevent erosion, to protect the newly built dams, to plant green belts around industrial zones and to increase forest productivity in general, and, particularly, the share of coniferous roundwood.

The first afforestation efforts date from 1884–1887 when an ordinance of the Ministry of Finance attempted to stop the arbitrary use of forests. Under the guidance of the French forester Félix Louis-Marie Vogéli, head of the Bureau for Reinforcement of Torrents in Kazanluk, anti-erosion afforestation was undertaken and about 4,000 ha of forest plantations were established, predominantly of coniferous tree species (*Pinus sylvestris* L., *Pinus nigra* Arn., *Pseudotsuga menziesii* Franco etc). The world economic crisis in 1929–1931 had an impact on afforestation in Bulgaria leading to a sharp decrease in new plantations due to the lack of funds.

After the end of World War II afforestation activities was aimed at reconstruction of low value and low productive forests with intensive management and establishment of plantations of faster growing and valuable tree species.

In this period mass afforestation began throughout Bulgaria. After 1950 afforestation with coniferous species was widespread in the lower forest belt, which is outside their natural range. The newly established plantations initially showed very good indicators: good establishment, fast formation of canopy and forest environment, rapid growth. Subsequently, when reaching 20–30 years of age (around the age of biological maturity), the stands showed the first shortcomings: reduced vigour, stand degradation, susceptibility to biotic and abiotic factors.

Now, due to the already advanced age (40–50 years) of the artificial plantations established in the 1960s and 1970s as well as the initiated processes of intensive degradation, their great ecological and economic value requires to take timely decisions on their future management.

Moisture as a limiting factor in the lower forest limit is crucial for the development of conifer plantations. For a given region, with the same rainfall, the moisture is redistributed mainly by the soil moisture retention potential. Evapotranspiration of conifers is higher in the lower forest belt, which further increases the deficit of soil moisture (Raev et al. 1991). Of great importance for conifers is also air humidity. In areas where it is higher conifers grow better. The following phenomenon is observed: peak growth of conifer plantations occurs much earlier than in plantations in conifers' natural range. The reason for this, according to Raev et al. (1991), is moisture as a limiting factor but other factors such as initial density, technology of establishment and cultivation should also be regarded as important ones.

In the lower forest belt soils are sufficiently supplied with nutrients for the undemanding Scots and Austrian pines. The limiting factor is moisture. This is the basis on which the concept of the transformation of coniferous plantations is built.

In the initial afforestation high densities of above 10,000 seedlings per 1 ha were used. The afforestation method showed a decrease in the density from 1×1 m to 1×1.5 m and subsequently around 1970 to 1×2 m, which meant that 5,000 saplings per 1 ha were planted. Planting at such densities involves reliance on significant self-pruning. In practice the density of planting is not much higher than that of natural regeneration. In plantations the same conditions lead to relatively uniform growth at a young age, lack of natural selection and, at a later age, to mass mortality.

In Bulgaria, Iliev and Doikov (1989) conducted studies of biometric indicators in Scots pine plantations at different density trials. At 13 years of age, they observed that the highest growing stock was obtained in a higher density (1×1.5 m), but the average diameter increment in trials with lower densities (2×2 m to 3×3 m) was twice as high as that in trials with the highest densities (0.75×0.75 m 0.5×1 m).

The first period of pine decline was at the end of the 19^{th} and the beginning of the 20^{th} century. Almost simultaneously degradation of Scots pine was observed in Germany in the 1920s and in Switzerland in the 1930s. For Bulgaria, Sirakov (1941) reported that a large part of the plantations in Sofia were damaged in 1924 and 1929, with Scots pine being severely affected. In the 1940s a new period of degradation was observed. During this period forests in Europe were reported to have deteriorated, with Scots pine being severely affected (Innes 1993).

The third wave of pine decline was reported in the 1960s and 1970s. Initially, the process was observed in Scots pine plantations in England, later in Switzerland and Germany (Zafirov 2008). Only after a few years of improvement in the forests' condition, a new period of pine decline was observed. The beginning of this decline was in the mid-80s. Innes (1993) reported the onset of pine decline in Scots pine forests at higher altitudes in Scotland. In central Europe, the process was widespread, covering Poland, the former Czechoslovakia, and the former East Germany.

In 2016 guidelines for the management of coniferous Scots and Austrian pine plantations were worked out at the national level; in them such plantations are classified into four groups according to their condition: high-risk, medium-risk, low-risk and sustainable. The main indicators for this classification are altitude, coefficient of mechanical stability, site quality and stocking. The implementation of these measures in recent years has led to results that cannot be considered completely satisfactory. Indicative of this has been the large share of sanitary cuttings and salvage logging in the coniferous forests in Bulgaria.

The concept of ecological compliance has been further developed into a comprehensive concept of the behaviour of ecosystems (and not just of organisms) called ecosystem fit. This is a concept that is based on the relationship between the actual (concrete) net primary productivity (NPP) of a given succession order and the theoretical maximum potential (TNPP). An important element, in addition to productivity, is the resilience of ecosystems formed during adaptation (Gordon et al. 1996).

In this concept the main combination is related to familiar concepts such as productivity and sustainability. The latter should be regarded as resistance to external influences (stability) and permanence over time, e.g. through constant regeneration (sustainability). Hence the basic idea of Gordon et al. (1996) for the use of ecosystem fit in predicting forest behaviour by linking productivity and diversity to the resilience of systems to natural disturbances.

Kostov (2014) suggest that ecosystem fit can be identified by considering two well-known and available parameters for each plantation: altitude and site type. They are presented in a coordinate system: the site type is plotted along the x-axis, and the altitude is laid off along the y-axis. It is accepted that differences of one degree in the site quality (richness or humidity) can be considered as one and the same type because they have a similar or the same forest growth effect. For example, the most common site for pine forests, B_2, almost coincides with C_1, while C_2 coincides with D_1, etc.

The intersection of the x-axis and y-axis is determined based on expert knowledge of the optimum for a tree species and the respective forest area. Figure 1 shows a graph for Scots pine in the Thracian Forest Region. In it the intersection point is at site $C_{1,2}$ and altitude of 1,250 meters (for the Moesian Forest Region it should be about 100 meters lower, and 100 meters higher for the Southern Border Region). The graph also shows several irregularly shaped, concentrically arranged areas. The centre indicates the potential zone (1) where the ecosystem fit of Scots pine plantations is most complete. It is between 1,000 and 1,500 m a.s.l., for sites from C_1 (B_2) to C_2 (D_1) in the Thracian Forest Region.

Zone (2) of the graph shows other sites and altitudes outside this optimum, where Scots pine naturally forms or participates in forest plantations (ecosystems), which in practice coincides with its potential natural distribution.

Zones (3) and (4) of the graph show altitudes and sites that are not characteristic of the natural distribution of Scots pine but where there are artificial plantations. Their ecosystem fit decreases the farther from the centre of the coordinate system they are located.

Together with the formation of the four zones numbered with Arabic numerals, the graph shows four quadrants numbered with Roman numerals. Each quadrant has some common features regardless of the zone (1–4). For example, quadrant I shows relatively high quality sites and high quality sites for Scots pine at altitudes above the optimum, while quadrant II shows the same sites but at altitudes below than optimum. In the different quadrants, the potential accompanying species or competitors of Scots pine will be different: e.g. in quadrant I they are fir, spruce, Macedonian pine, etc., and in quadrant II common beech, sycamore, hornbeam, oak, etc.

The other quadrants, III and IV, can be analyzed in a similar way; the combinations of quadrants and zones are 16 in total and are unambiguously defined. It can be assumed that in the general case the plantations occupying a given zone and quadrant will have the same or similar ecosystem fit, i.e. the same or similar resilience, productivity and behaviour in the past and in the future. This will allow differentiating and standardizing silvicultural objectives and interventions. Here's the examples with Scots pine (Figure 1).

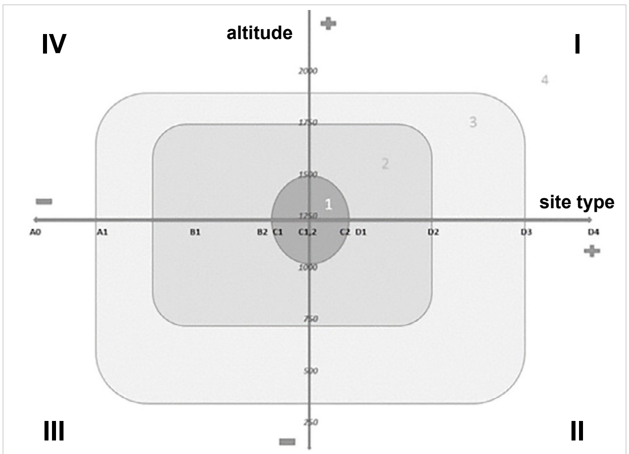

Figure 1. Influence of climatic factors on the condition and growth of artificial and natural plantations of Scots pine in the territory of the Southwestern State Enterprise (adapted by Kostov 2014)

The rugged terrain in Bulgaria, the climate and vegetation diversity are the main reasons for the different site conditions and zones of vulnerability to the changing climatic conditions.

Stein (1988) points out the four most important factors that affect the spread of *P. ponderosa*: temperature (of air and soil); humidity; competition with shade-tolerant tree species and fire. Low temperatures determine the upper limit of the species distribution by limiting mainly the growth processes. On the other hand, available humidity is important in determining the lower limit of distribution (Schubert, 1974). The author compares seven meso-topographic and microsite indicators, giving a rank for each of them: northerly aspect = 0, southerly aspect = 180; slope in %; soil temperature in °C; rocky soil as a value range between 0–30 (very rocky); humidity as 0–100 (very humid); light as 0–30 (a lot of light) and relief form (landform) as 0–10 (ridge).

Material and methods

The subject of research

A very large part (87%) of the artificial Scots pine plantations is below 1,300 m a.s.l., and about 30% of them are below the altitude of the species natural distribution in Bulgaria (Panayotov et al. 2016). About the location of the natural range, Popov et al. (2018) state that the distribution of the area of natural seed stands by altitude can be considered representative. Natural forests of Scots pine are found in the Rila-Rhodope massif over 700 m a.s.l., with 91% of them growing at 1,000–1,900 m a.s.l. (Panayotov et al. 2016). The altitude distribution of Scots pine plantations in the Southwestern State Enterprise is similar. More than half of the plantations, 79.3%, were established below 1,200 m a.s.l., with 53.2% being below the altitude of the species natural distribution. Scots pine forests within the territory of the Southwestern State Enterprise account for 42.7% of Scots pine forests in Bulgaria. They are also representative in terms of the ratio of natural stands and plantations.

Methods

Identification of vulnerability zones of forest plantations

Vulnerability is the extent to which a system is vulnerable and unable to cope with the adverse effects of climate change, including its extreme manifestations. Vulnerability is a function of the change of climate characteristics to which a system is exposed, its sensitivity and ability to adapt. For forest ecosystems the main effect of climate change is drought (Lindner et al. 2008). The vulnerability zones of forest ecosystems in Bulgaria are defined using different indices: De Martonne, Budyko, Selyaninov and Holdridge. For forestry purposes, the most suitable for use is the De Martonne humidity index (Alexandrov 2011, Raev 2015). According to Baltas (2007), this index is only applicable at the local level, so we use it in the present study. The formula for determining the drought index of De Martonne (1926) is as follows:

$$IDM = \frac{P}{T+10}$$

where

P is the average annual amount of precipitation, mm;

T is the average annual air temperature, °C.

The vulnerability zones according to the values of the De Martonne index (1926) are presented in Table 1.

Table 1. Vulnerability zones according to the values of the De Martonne index

IDM	Climate classification	Forest vulnerability zones	
		Notation *	Vulnerability level
10–25	Semi-arid	A	Very high
25–30	Moderately arid	B	High
30–35	Slightly humid	C	Medium
35–40	Moderately humid	D	
40–50	Humid	E	Low
50–60	Very humid	F	
≥ 60	Excessively humid	G	From medium to very high

* Zone A – permanent moisture deficit leading to deforestation; Zone B – permanent moisture disturbance; Zone C – moisture disturbances in occasional years; Zone D – minor moisture disturbance in occasional years; Zone E – optimal humidity conditions; Zone F – optimal humidity conditions; Zone G – gradual deterioration of environmental conditions due to excess moisture. (Raev 2015).

In determining the De Martonne index, the data used were data forecasting average monthly temperatures and total precipitation from the available climate data generated by the ClimateEU v.4.63 software package (Marchi et al. 2020) according to the methodology of Wang et al. (2016).

Data on average temperatures and precipitation at the plantation level were obtained from the project. The raster data sets were designed in WGS84 UTM 35N, which is the coordinate system used for the database of forests in Bulgaria. Global climate data have a spatial resolution of 1×1 km. These are the most recent forecast climate data from the Global Climate Model (CGM) used in the IPCC report (IPCC AR5. 2014, IPCC. 2014). GIS environments use procedures to retrieve aggregate statistics and append multiple attributes. The forest database was obtained from the Executive Forest Agency in Sofia.

Determination of ecosystem fit

The data used was obtained from the forest management plans of Scots pine forests of all territorial units within the Southwestern State Enterprise (EFA 2019). The database was processed in Microsoft Excel and various data were extracted in tabular and graphical form.

To verify the adequacy of the classification of ecosystem fit of Scots pine plantations proposed by Kostov (2014), it was decided to assess the two main components in the classification plotted as ordinates and abscissas. Kostov (2014) suggests placing the site type along the x-axis and the altitude along the y-axis. To be able to apply this approach and to consider the main components influencing the growth conditions, it was necessary to use indices as aggregate characterization. Dukhovnikov (1974, 1975) suggests two indices: relief complex (RC) and soil complex (SC).

The main relief elements that fully characterize the climate in a single plantation/stand are altitude, slope of the terrain, aspect and relief form (landform). The following data on the relief elements were used in the present study:

1. Slope of the terrain: it is expressed by the additional angle up to 90°, the most favourable slope (0°) in terms of soil moisture receives the highest numerical value.
2. Aspect: the aspect scale ranges from 20 to 90 as follows: southerly – 20, southwesterly – 30, southeasterly – 40, westerly – 50, easterly – 60, northwesterly – 70, northeasterly – 80, northerly – 90. It is necessary to assess surrounding shade, and, based on that, a southerly aspect may change to a northeasterly or even to a northerly aspect.
3. Relief form (landform) of the terrain: ridge – 20; slope (upper part) – 35; slope (lower part) – 55; plain or plateau – 70; depression – 90.
4. Altitude is determined by DEM in GIS environment with an accuracy of 1 m. The numerical index of this indicator is calculated by reducing 10 times the actual altitude.

The relief complex **RK_Index** is the average of the above four indicators (Duhovnikov 1975). Therefore, its average value is the sum of the average values of the indicators used in the calculation.

The site quality index, **SQ_Index** is used to assess the site conditions; it is calculated as the average of the numerical values of the following indicators:

1. Soil Nutrient Richness: very poor (A) – 20; very poor to poor (AB) – 40; poor (B) – 60; poor to relatively rich (BC) – 80; relatively rich (C) – 100; relatively rich (CD) – 120; rich (D) – 140.
2. Depth: very shallow – 20; very shallow to shallow – 30; shallow – 40; shallow to medium deep – 50; medium deep – 60; medium deep to deep – 70; deep – 80; deep to very deep – 90; very deep – 100.
3. Moisture: very dry – 40; very dry to dry – 60; dry – 80; dry to slightly moist/fresh – 100; fresh/slightly moist – 120; fresh/slightly moist to moist – 140; moist – 160; moist to wet – 180; wet – 200; wet to waterlogged – 220; waterlogged – 240.
4. Soil compaction: loose – (+20); compacted – (–20); heavily compacted – (–40).
5. Degree of erosion: without erosion – 0; I degree – (–10); II degree – (–20); III degree – (–30); IV degree – (–40).

Bogdanov (1975) suggests that a common index, serving as a quantitative assessment for the site conditions, can be made from the two indices by multiplying the two complex indicators: the relief complex, RK, and the soil complex, PK. In our study, this index is called the total index, ALL_Index and is calculated as an arithmetic mean.

The following statistical methods were used: Regression analysis was applied for generating and comparing the regression dependences between the coefficient RK_Index and the altitude of natural and artificial plantations. Hypotheses for differences between the two models were tested via Chow's test using the functions of the R-package gap (Zhao J.H., 2019). Visualization of data variation in different groupings was represented using the functions for box-plot diagrams of the R-package ggpubr (CRAN 2019).

Generation of a convex hull for a given subset of data. The convex hull in the two-dimensional visual is the contour that covers the smallest possible area while encompassing all points in the set. The shape's construction was performed by using the chull function of the R-package grDevices (R Core Team 2019), which generates the shape according to the algorithm of Eddy (1977).

The ABC analysis was applied to divide the values of a vector into three classes: A, B and C depending on their contribution to the cumulative sum. The algorithm is described in (Ultsch and Lotsch 2015) and is applied in the R-package ABC-analysis. Generalized visualization of the results of the ABC grouping, convex hull, etc. through the Grammar of Graphics functions in the ggplot2 R-package (Wickham 2016). The studied indices represent the average values of several indicators, which is why the formula for dispersion of a sum of random variables as a sum of the elements of the respective covariance matrix was applied for measuring the decomposition of the variance (Molle 2012).

Results

The majority (55.8%) of the artificially established Scots pine plantations occupy the highly vulnerable zones A and B (De Martonne 1926). Zone B also includes 16.1% of the natural Scots pine stands. About ⅓ of the Scots pine forests in the Southwestern State Enterprise, with almost equal shares of natural and artificial plantations, occupy zone C. The zones of optimal climatic conditions and low level of vulnerability (zones D and E) are occupied by 47.8% of the natural Scots pine stands and only 13% of the plantations (Figure 2).

Climatic conditions in these zones are characterized by continuous drought during the growing season ranging from 2–3 months (June to September) in zone A to 1.5 months (August and September) in zone B (Figure 3).

Zone C includes natural stands and plantations growing between 1,000–1,200 m a.s.l.; now the climate conditions in this zone are relatively favourable for the development of forest ecosystems, but it can be expected that in drought conditions moisture shortage will occur, especially

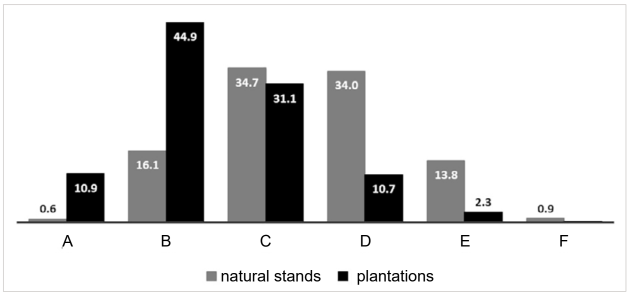

Figure 2. Percentage distribution area of pine forests areas by the De Martonne index

Natural stands are marked in grey, plantations are marked in black

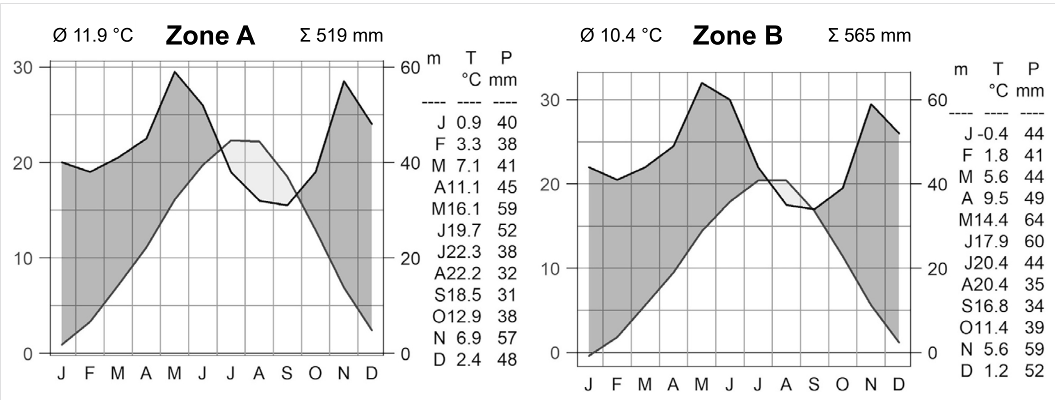

Figure 3. Climate Diagrams for Zone A (left) and Zone B (right)

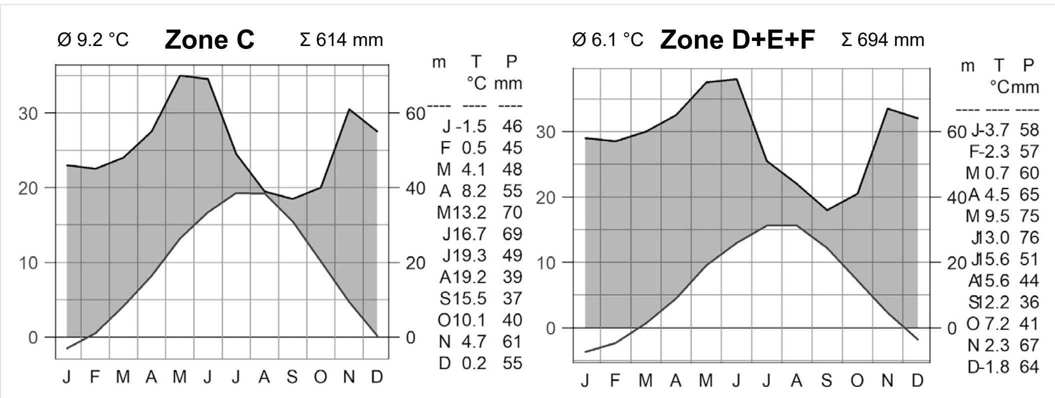

Figure 4. Climate Diagrams for Zone C (left) and Zones D+E+F (right)

during the growing season, which will adversely affect the growth and development of these forests. Zones D, E and F are characterized by optimal conditions for the development of Scots pine plantations with a very low risk of drought (Figure 4). The plantations in these zones grow at altitudes above 1,200 m.

Ecosystem fit

The classification by ecosystem fit of Scots pine plantations suggested by Kostov (2014) has two main components characterizing the conditions (site type and altitude) for growth plotted along the x-axis and y-axis.

As the artificially established plantations grow under conditions that are predetermined by the choice of afforestation sites, it was decided to consider the plantations by origin; the data were processed separately for plantations and natural stands. Standardized scales were used, with the SQ_Index along the x-axis, and the RK_Index along the y-axis (Figure 5).

The figure shows the absolute appropriate location of the plantations by site type (Pogrebnyak 1955, Chertov et al. 2018), starting from poor and very dry (A_1) and moving to rich and wet (D_3), from left to right along the x-axis. It should be noted that the x-axis denoted for the artificial stands (the dotted line) is shifted downwards, as the Scots pine plantations were established at low altitudes, which is atypical to the species natural distribution (Figure 5). Therefore, the resulting x-axis had to be used for the naturally occurring Scots pine forests, where the altitude distribution remains unaffected by artificial, or man-made, intervention. From a practical point of view, it is of interest to understand what the shift in altitude is when considered in its absolute value.

Since altitude is an addend, when forming the RK-Index, the axis shift is equal to the difference between the average values of the two altitudes, i.e. 213.5 m.

The method applied to assess the influence of the individual components in the making of the indices, was that of decomposition of the variance into a sum of random variables. For the two origins, the decompositions of the variances are given in Table 2 and are based on the variables constituting the RK_Index.

The order of variables by percentage in total variance matches the order of variables with RK_Index by correlation coefficient. Altitude plays the most important role in the formation of the relief index, followed by aspect, which is also a redistributing factor for growth conditions. The relief form and the slope of the terrain exert significantly less influence, but in the case of plantations, the slope of a hill is still important because most afforestation is done with the purpose of anti-erosion or overall strengthening.

When studying the influence of the individual components involved in the calculation of the SQ_Index, the components of the index variance depending on the origin are shown in Table 3. The greatest influence, over 40%, on

Table 2. The decompositions of the variances on the indicators forming RK_Index

RK_Index	Altitude	Aspect	Relief	Slope
Plantations	50.4%	40.6%	5.9%	3.2%
Natural stands	50.0%	42.0%	8.0%	0.0%
Correlation coefficients, plantations	0.64	0.58	0.19	0.17
Correlation coefficients, natural stands	0.61	0.59	0.25	–0.01

Table 3. Influence of the individual components involved in the calculation of the SQ_Index

SQ_Index	Richness	Depth	Moisture	Compaction	Erosion
Plantations	45.9%	18.3%	27.2%	1.8%	6.7%
Natural stands	44.5%	21.8%	26.9%	1.6%	5.1%
Correlation coefficients, plantations	0.96	0.81	0.85	0.17	0.52
Correlation coefficients, natural stands	0.95	0.87	0.84	0.19	0.49

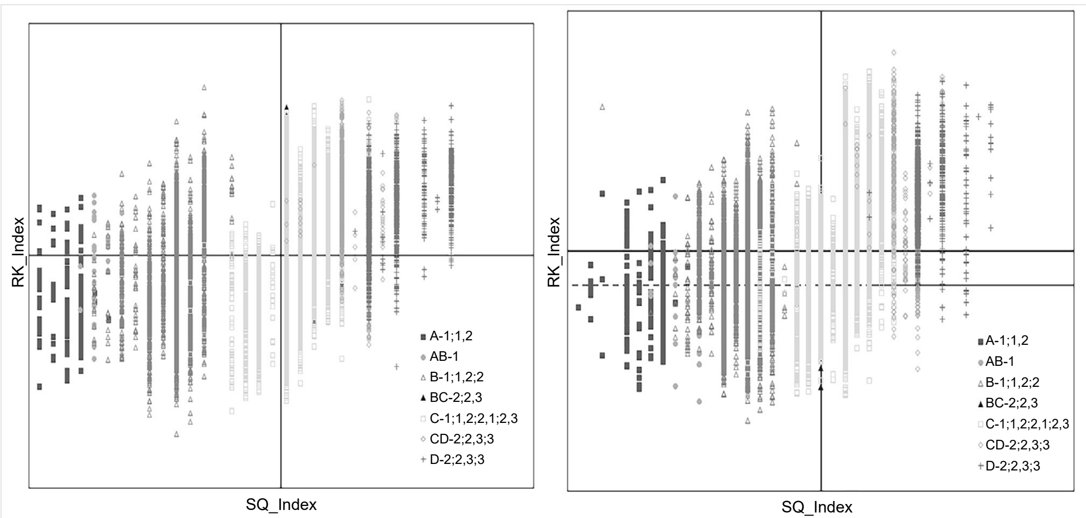

Figure 5. Distribution of SQ_Index and RK_Index by site types for natural stands (left) and plantations (right)

the total dispersion has soil richness, followed by moisture and depth. Soil compaction and the degree of erosion have less influence, below 10%.

Since the plantations established on eroded terrains or natural stands on such terrains are a very small number compared to all other cases for assessment of the influence of the erosion indicator, it was decided to assess the influence of individual components on the dispersion by analyzing plantations with erosion processes separately.

The presence of erosion significantly changes the influence of the other components (Table 4). The richness of the soil still has the greatest influence, but the influence of the moisture indicator becomes insignificant (below 3%) at the expense of the increased influence of the indicator of erosion, soil depth and compaction.

The diagram for variation of the values of ALL_Index by site type (Migunova 2017, Pogrebnyak 1955) is presented in Figure 6.

The average of the index increases as the soil richness increases, i.e. a higher value of the index corresponds to better conditions for plantation development and there is almost no overlap. For this reason, we use the total index ALL_Index as a quantitative indicator for assessing site conditions. ABC analysis was applied to group the plantations by using this index. This approach allows the plantations to be classified according to the value of the total index ALL_Index. The first group, group A, includes those plantations situated in the best site conditions, group C includes the plantations growing in the worst site conditions, and group B those plantations that can be found in the middle (Figure 7).

Similarly, to the proposed conceptual classification of ecosystem fit by Kostov (2014), we obtained two diagrams for a classification according to the ecosystem fit of the Scots pine natural stands and plantations in the South-western State Enterprise. The diagrams show three groups of plantations, marked by different colours depending on which of the three groups obtained by ABC analysis they fall in (Figure 8).

Quadrant I includes plantations growing on rich and slightly moist/fresh or slightly moist/fresh to moist site conditions and at high altitudes. In quadrant II, the plantations are located at the same altitudes as in the quad-

Table 4. Influence of the individual components involved in the calculation of the SQ_Index

SQ_Index	Erosion	Richness	Depth	Moisture	Compaction	Erosion
Plantations	no erosion	44.8%	23.9%	30.4%	0.9%	-
	with erosion	32.2%	26.0%	3.0%	16.7%	22.0%
Correlation coefficients	no erosion	0.95	0.92	0.85	0.1	-
Correlation coefficients	with erosion	0.84	0.74	0.24	0.36	0.8
Natural stands	no erosion	44.1%	26.3%	28.9%	0.7%	-
	with erosion	36.2%	26.4%	1.7%	13.1%	22.6%
Correlation coefficients	no erosion	0.94	0.94	0.83	0.10	-
Correlation coefficients	with erosion	0.84	0.74	0.24	0.36	0.80

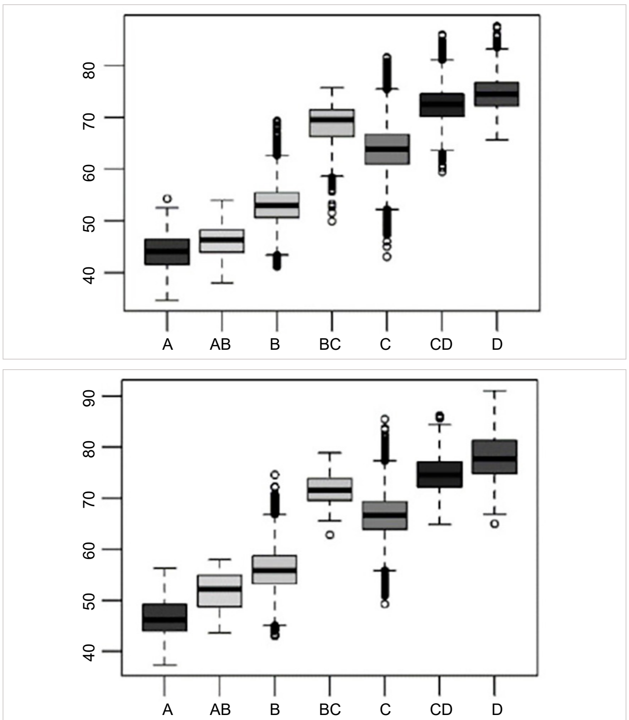

Figure 6. Box-plot diagrams for ALL_Index by site

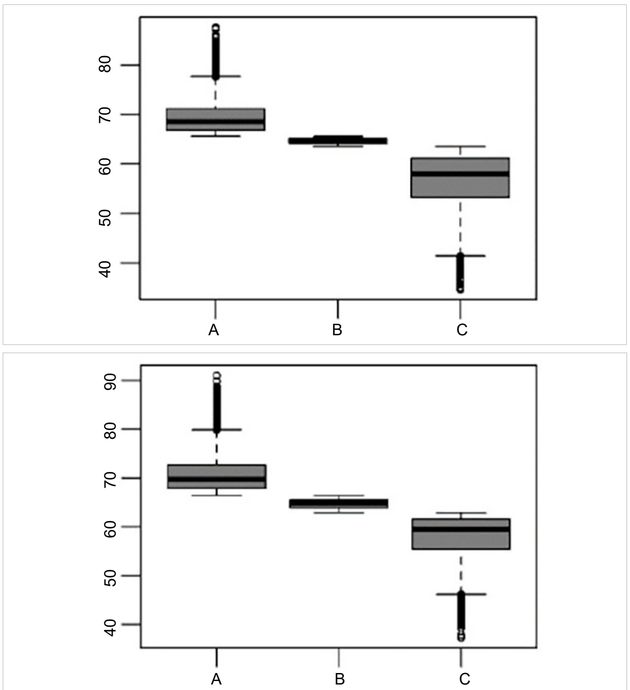

Figure 7. Box-plot diagrams for ALL_Index by groups of ABC analysis

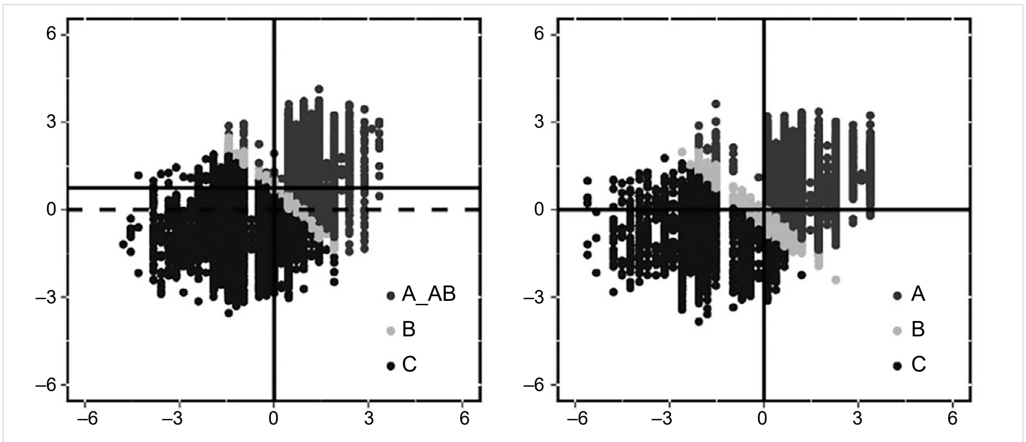

Figure 8. A classification according to the ecosystem fit of Scots pine natural stands (on the right) and plantations (on the left) in the Southwestern State Enterprise

rant I, but they grow in poor or very poor, dry or very dry conditions. In quadrants III and IV the site conditions are like these in quadrants II and I, but the plantations are located at lower altitudes. To the extent to which soil richness can partially compensate for the lack of atmospheric humidity (quadrant IV) and, conversely, high atmospheric humidity partially compensates for poorer soil conditions (quadrant II), it can be assumed that these two quadrants are characterized by intermediate growth conditions. Quadrant III includes plantations outside any ecosystem fit into the environment because in it there are poor and very poor and dry site conditions combined with low humidity.

Figure 9 shows the intervals of variation of the total index ALL_Index by quadrant and groups of ABC analysis.

In groups B and C of natural stands there is a partial overlap of the intervals of variation of the total index (Figure 9.) To simplify the further classification, it was decided the stands of groups B and C to be analysed together. In the case of plantations, there is no overlap in the intervals of variation, but the very narrow interval for the plantations of group B is much closer to the lower value of the variation of the interval of group A. Therefore, in plantations it was decided the two groups A and B to be analysed together. The intervals of variation of the newly formed groups are shown in Figure 10.

In this way the proposed classifications were simplified by forming two groups of plantations located in four quadrants as follows (Figure 11).

Data on the percentage distribution of the area of natural stands and plantations by the quadrants, groups of ABC analysis and vulnerability zones according to De Martonne are shown in Tables 5 and 6.

The climate diagrams show that most Scots pine plantations in the Southwestern State Enterprise grow in conditions of continuous drought during the growing season.

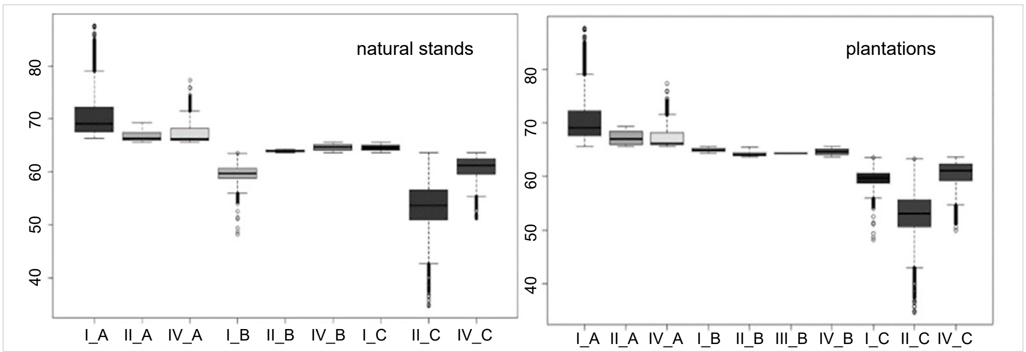

Figure 9. Box-plot diagrams for distribution of ALL_Index by quadrant and groups of ABC analysis. Natural stands are on the left, plantations are on the right

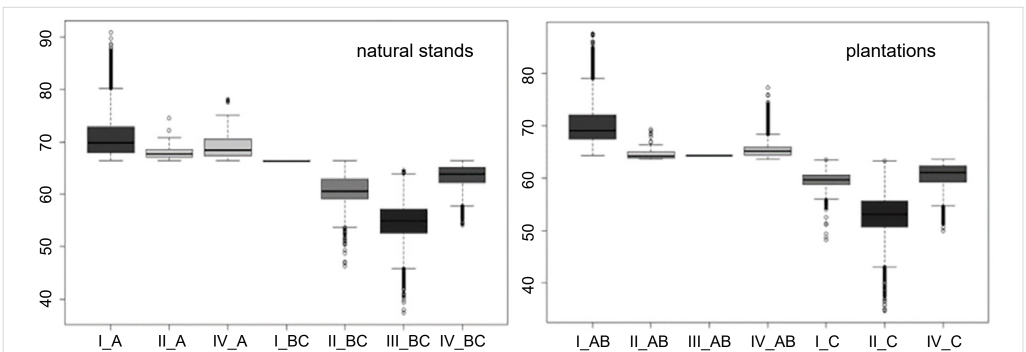

Figure 10. Box-plot diagrams for distribution of ALL_Index by quadrant and groups of ABC analysis

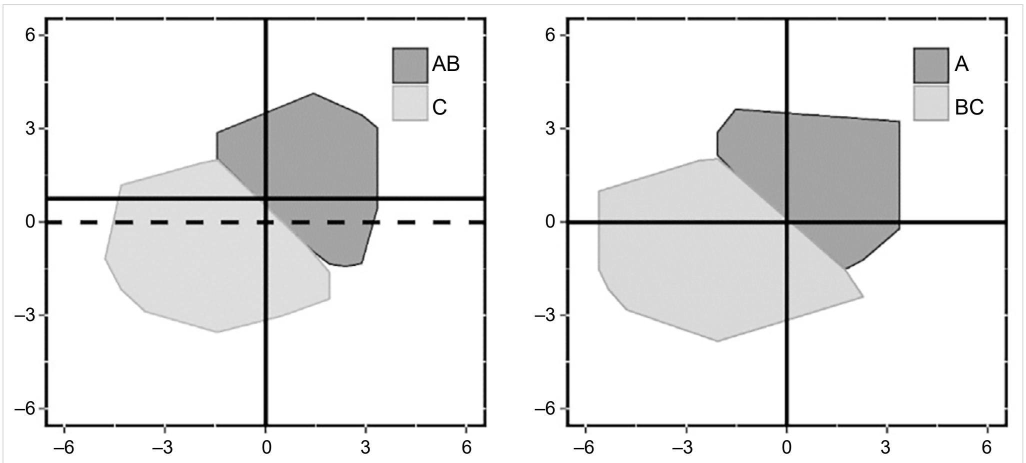

Figure 11. A classification according to the ecosystem fit of Scots pine natural stands (right) and plantations (left)

Table 5. Distribution of the area of plantations by the quadrants, groups of ABC analysis and De Martonne zones

Quadrant	De Martone zone								TOTAL
	A	B	A+B	C	D	E	F	D+E+F	
I	**0.1**	**4.6**	**4.7**	**6.7**	**5.1**	**1.5**	**0.0**	**6.6**	**18.0**
group A	0.1	4.6	4.7	6.7	5.1	1.5	0.0	6.6	18.0
II	**0.2**	**0.8**	**1.0**	**0.6**	**0.3**	**0.2**	**0.0**	**0.4**	**2.0**
groups A+B	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.3
group C	0.1	0.7	0.8	0.6	0.2	0.2	0.0	0.4	1.7
III	**8.9**	**18.4**	**27.4**	**7.1**	**0.8**	**0.1**	**0.0**	**1.0**	**35.5**
group B	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1
group C	8.9	18.3	27.2	7.1	0.8	0.1	0.0	1.0	35.3
IV	**1.6**	**21.1**	**22.8**	**16.7**	**4.5**	**0.5**	**0.0**	**5.0**	**44.5**
groups A+B	0.4	7.9	8.3	6.9	2.4	0.4	0.0	2.8	18.0
group C	1.2	13.2	14.4	9.8	2.1	0.1	0.0	2.2	26.5
TOTAL	**10.9**	**44.9**	**55.8**	**31.1**	**10.7**	**2.3**	**0.0**	**13.0**	**100.0**

Table 6. Distribution of the area of natural stands by the quadrants, groups of ABC analysis and De Martonne zones

Quadrant	De Martone zone								TOTAL
	A	B	A+B	C	D	E	F	D+E+F	
I	**0.8**	**12.7**	**13.4**	**18.4**	**16.0**	**4.8**	**0.4**	**21.3**	**53.1**
group A	0.8	12.6	13.3	18.3	15.8	4.8	0.4	21.1	52.8
group B	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.4
II	**0.0**	**0.8**	**0.8**	**2.0**	**2.3**	**0.4**	**0.0**	**2.6**	**5.4**
group A	0.0	0.0	0.0	0.1	0.3	0.1	0.0	0.4	0.5
group B+C	**0.0**	**0.8**	**0.8**	**1.9**	**2.0**	**0.3**	**0.0**	**2.3**	**4.9**
III	**0.1**	**1.3**	**1.4**	**4.2**	**2.6**	**0.2**	**0.0**	**2.9**	**8.5**
group C	0.1	1.3	1.4	4.2	2.6	0.2	0.0	2.9	8.5
IV	**0.6**	**8.9**	**9.5**	**13.1**	**8.3**	**1.9**	**0.1**	**10.4**	**33.0**
group A	0.0	0.7	0.7	0.9	1.0	0.1	0.0	1.1	2.7
group B+C	0.6	8.2	8.8	12.2	7.3	1.8	0.1	9.3	30.3
TOTAL	**1.5**	**23.6**	**25.1**	**37.8**	**29.2**	**7.3**	**0.6**	**37.1**	**100.0**

Even plantations in group A, which grow under favourable site conditions, will, in certain dry years, experience physiological stress during the growing season. These account for 31% of the area in zone C of De Martonne.

The data presented in Table 6 shows that, unlike plantations, the area of the natural stands of Scots pine in quadrant I, which has the best conditions for the development of the species, is 53.1%. Only ⅓ of the natural stands are in quadrant IV, which is characterized by rich and relatively rich site conditions but also by risk of short-term drought during the growing season. Quadrant III, which is characterized by the most unfavourable site conditions, includes 8.5% of the natural Scots pine stands, which develop under the conditions of one-month-long drought during the growing season (Appendix 1). This insignificant area unequivocally confirms that natural Scots pine stands with lack of ecosystem fit and high drought vulnerability are less than 10%, in contrast to plantations for which ½ of the them are under threat.

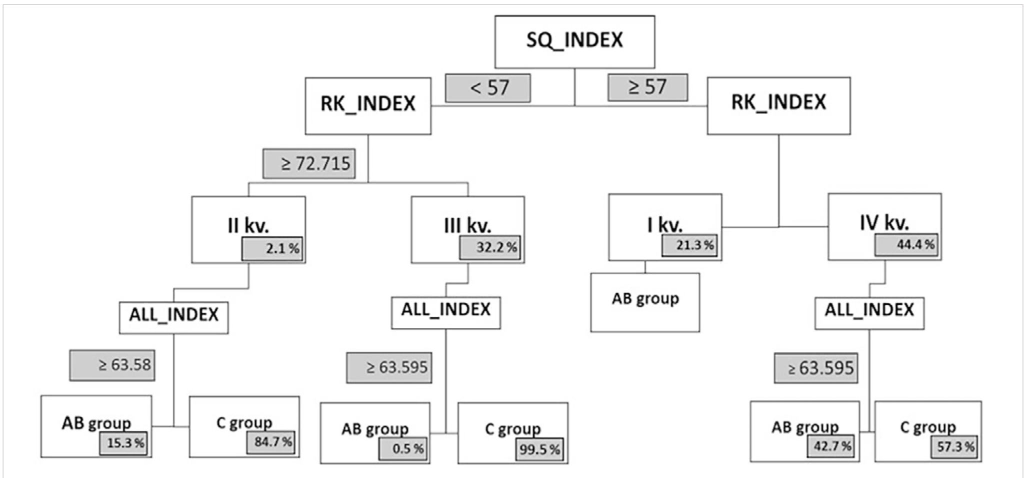

Figure 12. A classification according to the level of ecosystem fit for Scots pine plantations in the Southwestern State Enterprise

Classification according to ecosystem fit

Based on the conducted research and in order to differentiate the silvicultural activities according to the level of ecosystem fit of the pine plantations in the Southwestern State Enterprise, we developed the following classifications by sequential construction of a classification tree and ABC analysis by quadrants.

On the basis of the values of the indices RK_Index and SQ_Index (Figure 12), a given plantation was placed in a corresponding quadrant. The bordeline values for the plantations' differentiation was 57.0 for SQ_Index and 72.715 for RK_Index. Using the two borderline values determined the quadrant of a plantation. The total index ALL_Index value was used to differentiate the groups according to the ABC analysis. When using the borderline values of 63.58 (quadrant I) and 63.595 (quadrant II, III, IV), 100% accuracy was obtained in determining the groups within the individual quadrants. From a practical point of view, this approach will facilitate the classification of plantations according to their level of ecosystem fit corresponding to one of the quadrants. Quadrant I, as well as group AB, includes the plantations with good ecosystem fit, and quadrant III, as well as group C. includes the plantations characterized by a lack of ecosystem fit to the site conditions. Quadrants II and IV comprise plantations with intermediate conditions, and in this situation, when determining a plantation's ecosystem fit, it is important to take into account whether it belongs to group AB or group C.

Discussion

The proposed classification for ecosystem fit is aimed at prioritizing management objectives and reducing the risks of loss of forest cover in the context of climate change. Under these conditions, natural disturbances (Panayotov et al. 2016, Popov et al. 2018) are enhanced in the plantations established at low and dense afforestation schemes. These phenomena will occur with increased frequency in the absence of ecosystem fit.

Plantations' reduced resilience leads to additional risks of increased fire danger and infestations and actually, in many cases plantations become less efficient and have lower productivity compared to natural forests. Therefore, disturbances caused by biotic and abiotic factors, especially in recent years, are significant. Disturbances caused by various factors are observed, which vary within certain limits, but are invariably present over the years. This phenomenon is typical of plantations across Bulgaria. Despite the early culmination of plantations, low rotations, inevitable replacement by native autochthonous vegetation leading to minimal share of coniferous species, conifer plantations need to be maintained at normal densities to ensure their resilience and to improve their productivity.

The "uniform" conditions in plantation establishment (Kostov 2014) largely neutralized the influence of factor variability on the discussed characteristics (indicators), and, therefore, the analyses were conducted separately, based on the plantations' origin. The absence of any thinnings leads to a number of negative phenomena in the pine plantations, especially in those in the lower forest belt/ such as: deterioration of the mechanical stability (the ratio height/diameter at breast height); high values of evapotranspiration; early culmination of growth; deterioration of soil properties; infestations; increased fire danger in coniferous forests in the lower belt; without thinnings, intermediate shrub layer is formed, and the return of economically valuable native tree species is delayed; late thinnings are more like sanitation cuttings than having selection purposes.

The share of sanitary and emergency cuttings has doubled in the last five years (2015–2020) (https://system.iag.bg/). While, under normal circumstances, sanitary and emergency cuttings account for about 25–30% of the total yield, in recent years their share has reached 65%. These statistics confirm the existing problem with Scots pine forests, which in recent years have suffered from abiotic and biotic problems.

More than half of the total area of the studied pine plantations are into a zone with permanent moisture deficit (A + B according to the De Martonne index), which confirms the studies of Raev et al. (1991), Lindner et al. (2008), Zafirov (2008), Popov et al. (2018) on the leading role of drought in climate change and its impact on the state of plantations. The Demartonne's C-zone is characterized by a high level of vulnerability, and, in periods of drought, forest ecosystems will be subject to a high level of stress (Raev et al. 2003). All Scots pine plantations growing below 1000–1,100 m a.s.l. fall into a zone of high vulnerability to drought (Raev et al. 1991).

The absence of timely and consistent thinnings in artificial (as well as in natural) coniferous forests is associated with potential losses of biomass and, particularly, of wood in the form of: 1) unproduced wood due to reduced increment in young, dense plantations, 2) wood that is lost because of tree mortality is, in general, left in the forest, and 3) wood that is lost because of significant disturbances by abiotic (fires, windthrow, ice and snow damage) and biotic factors (pest infestations and fungal diseases), which makes it completely or largely unusable (Popov et al. 2018). Therefore, it is necessary to carry out the necessary activities in the plantations that are outside ecosystem fit (quadrant 3, group C of quadrants 2 and 4).

Only 18% of the plantations' area falls in the zone of optimal fit in quadrant I (Table 5). Considering that 4.7% of them are in the highly drought-vulnerable zones of De Martonne, we can conclude that only 13% of plantations are situated in an optimal ecosystem fit. Outside any ecosystem fit and under extremely unfavourable site conditions are 35.5% of the plantations of the Southwestern State Enterprise. Approximately ½ of the artificially established plantations are in the intermediate quadrants II and IV. Under good site conditions, but at low altitudes and, therefore, vulnerable to drought, are 44.5% of the plantations. Only 12.8% of plantations grow under optimal climatic conditions and can develop and survive in the long run. In the rest of the plantations, it is necessary to begin transforming the species composition using native tree species. This is extremely important for plantations of quadrant III, group C and quadrant IV, group C, which are 42% of the area of plantations in the Southwestern State Enterprise.

Conclusions

In the management of Scots pine plantations, it is extremely important to consider that they are anthropogenic ecosystems and the processes that take place in them differ in certain respects from those in natural forest ecosystems. This study confirmed the need to determine the ecosystem fit of artificial Scots pine plantations in the Southwestern State Enterprise. The proposed numerical characteristics for assessment of growth conditions such as relief complex (RK_Index) and soil complex (SQ_Index) as well as their graphical representation allow to classify plantations according to their level of ecosystem fit. All this will allow to proceed to a differentiated approach to the future management of these plantations and for science-based definition of objectives.

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Appendix 1. Climate Diagrams by quadrant for Scots pine plantations