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Silver Fir Decline in Pure and Mixed Stands at Western Edge of Spread in Croatian Dinarides Depends on Some Stand Structure and Climate Factors

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Abstract: Silver fir is one of the most threatened conifer species in Croatia, especially at the western edge of its spread in Croatian Dinarides, where the decline in fir trees has resulted in significant ecological and economic issues. The aim of this study was to determine, over an 18-year monitoring period, the relationships of silver fir crown defoliation with climatic factors and structural attributes. We further analyzed the tree retention time in a given defoliation class and transition dynamics between defoliation classes, as well as the survival/mortality of trees. Data on silver fir defoliation were analyzed in two different forest types: in pure silver fir and in mixed silver fir and common beech stands. The climatic factors, primarily vegetation period air temperature, potential evapotranspiration, and dry season water deficit, were correlated with crown defoliation. Regarding the structural attributes, in the mixed stand with predominantly smaller trees, crown defoliation increased with reduced diameter at breast height, crown diameter, social class, and crown illumination. In the pure fir stand, crown defoliation increased with reduced crown diameter, greater crown asymmetry, greater crown illumination, and on trees with a stork's nest crown. The retention time in defoliation classes differed for research sites. Transition dynamics were different only for trees in the highest defoliation class (dead trees). At the end of the study period, silver fir mortality was higher in the pure fir stand. Increased silver fir defoliation and mortality can be expected in the future, particularly in overmature stands under prolonged drought stress. Permanent forest monitoring could ensure the high-quality data needed for adaptive management of fir stands that could positively influence the structure of these stands and, thus, improve their health status.

Keywords: silver fir; crown defoliation; mortality; climate; stand structure

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1. Introduction

During their life cycle, trees are exposed to individual and combined stresses of varying intensity and duration. Tree vitality can be defined as the capability of a tree to assimilate, survive stress, and react to changes in environmental conditions [1]. Multiple factors influence tree vitality, and the reasons for the deterioration in the condition of certain tree species or stands must be sought in the specific interactions of numerous stress factors. In any case, long-term stress weakens trees, reducing their vitality [2].

Given that global changes include a modification of ecological factors, with simultaneous changes in the intensity of various stressors, understanding how plants adapt to stress is key in understanding the influence of climatic and habitat conditions on vegetation. In particular, climatic factors are considered critical for tree condition, as they determine the availability of water in terms of its uptake and transport in trees, while a lack of water causes a loss of vitality. Forest ecosystems today are under highly complex stand and ecological conditions, as evidenced by the disturbed stand structure and physiological weakening and dieback of trees [3,4]. The influence of stand structure on tree condition has not been the subject of research very often, but several authors have discussed the relation between various structural attributes and tree vitality. Spathelf [5] found a significant correlation between crown defoliation and diameter; Dobbertin and Brang [6] found that the crown defoliation of various forest tree species in Switzerland, among them silver fir, was related to the social position of the trees, and Oliva and Colinas [7] mentioned stork's nest as one of the decline symptoms that coincides with defoliation in the silver fir decline process. Silver fir (*Abies alba* Mill.) is one of the most valued conifer species in Europe, both for historical and economic reasons [8–10]. This is also true for the Dinaric region [11], and therefore, the need to better understand the processes related to silver fir dieback arises. This species is sensitive to a number of unfavorable factors, such as increasing air temperature and lack of precipitation due to climate change [12,13], air pollution [14,15], unfavorable biotic factors [16,17], and inappropriate forest management [3,18]. Silver fir has a long history of decline in the Mediterranean region [7,19], particularly in southeast Europe [20] and in the Dinaric region [21–23]. The intensity of fir decline varies throughout east and southeast Europe due to the many combinations of causes of dieback [24]. With increasing warming and dryness, changes in the ecological niche of silver fir can be expected in the Dinarides [25,26], where a shift in silver fir distribution towards higher elevations is expected [27].

With regard to crown defoliation, silver fir is the most threatened conifer species in Croatia, and silver fir decline has resulted in significant ecological and economic issues in certain regions of Croatia. Studies in the Dinaric region of Croatia have indicated significant damage and deterioration of the silver fir stands [28–30].

According to the Manual of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) [31], defoliation is defined as the loss of leaves in the assessed part of the crown in comparison to a reference tree. Since tree defoliation is affected by abiotic [32–35] and biotic factors [34,36,37], it is applicable as an indicator for multiple stress factors [38]. Meanwhile, crown defoliation is the consequence of tree condition over the past few growth years, which may hinder the use of defoliation as a stress indicator for assessing current tree vitality [39]. Climate variability in the year preceding the assessment year was found to account for 79% of the variability of the current defoliation [40]. This implies that defoliation values do not reset every year; in fact, it takes several years after a significant stress (e.g., a drought year) for defoliation values to return to pre-stress levels, though this is also species-dependent. Defoliation of trees can change from year to year, and it can suddenly increase after a severe stress event (such as drought) [41]. Trees can recover from the loss of leaf mass, although the duration of recovery to pre-stress levels depends on both the species and the environmental conditions, and therefore, not every increase in defoliation can be associated with a permanent decline in vitality. Erdle and MacLean [42] confirmed that crown defoliation causes a reduction in the proportion of surviving trees. According to Manion [43], the mortality spiral illustrates the series of events that lead to tree mortality, and defoliation is one of these events. Crown defoliation is an important factor in the tree mortality model, as mortality increases with increasing crown defoliation [6,44]. Bigler et al. [45] reported that severe crown defoliation of silver fir is often associated with its decline. However, the nature of the relationship between defoliation and mortality, and the factors involved, are not yet fully understood. Our hypotheses were, thus, as follows:

(a) Unfavorable climatic conditions, especially drought, have a detrimental impact on silver fir defoliation, leading to tree mortality;
(b) Tree vitality and development depend on stand structure.

Trees in edge populations are likely to respond more dramatically to climate change than those in the main range of the species [46–48]. The aim of this study was to investigate, during a long-term observation period, the relations of climate and stand structural attributes with crown defoliation, tree mortality, and the duration of each defoliation stage through a comparison of the two most common silver fir forest types in the Dinaric region of Croatia. This insight is important for the consideration of various factors influencing silver fir vitality and development in the whole of Europe.

2. Materials and Methods

2.1. Study Site

The study was conducted in the Western Dinarides, in the mountainous region of Croatia, within beech-fir and fir forests. The study site has a moderately warm rainy climate without dry periods (Cfsbx climate type according to the Köppen Climate Classification). The average mean air temperature in the study area is 7.2 °C, and the mean annual precipitation is about 2000 mm [49]. In Croatia, silver fir occurs in two common types of forest communities: fir with hard fern (*Blechno-Abietetum* Ht. 1950) and the Dinaric beech-fir forests of the Western Dinarides (*Omphalodo-Fagetum* Marinček et al., 1993). The differences between them are reflected mainly in the site conditions and stand structure. In the association of silver fir with hard fern, silver fir is the main tree species growing in a selection group structure on silicate bedrock and dystric cambisol or podsol soils with low to very low pH, mostly in the altitudinal range of 650 to 900 m [50]. The Dinaric beech-fir forests of the Western Dinarides grow on limestone and dolomite, on shallow and skeletal cambisols, or illimerized soils, in the altitudinal range from 600 to 1300 m. The forest stands are selectively managed and have a single-tree structure [3].

2.2. Measurement of Structural Stand Attributes in the Experimental Plots

Two permanent experimental sites were established, representing the two most common silver fir forest types in Croatia: pure silver fir stands in association with hard fern at the Brloško site (site A, 45°20′06″ N and 14°39′32″ E) and beech-fir stands of the Western Dinarides at the Bitoraj site (site B, 45°16′47″ N and 14°47′33″ E) (Figure 1). Four experimental plots, 50 × 50 m in size, were set up at each site, for a total of eight experimental plots (2 ha). Experimental plots (repetitions) were chosen to represent each forest association in terms of the number of trees and growing stock (Table 1).

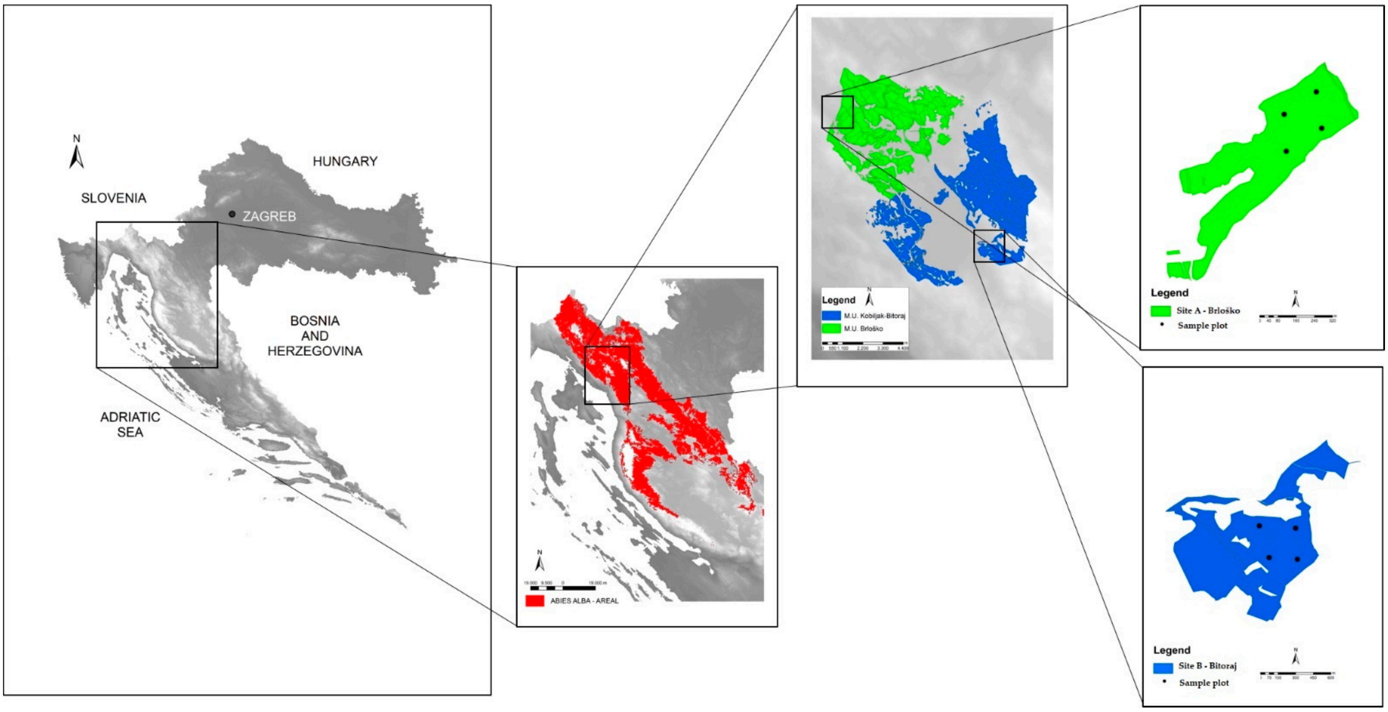


Figure 1. Locations of study sites and plots.

Table 1. Site and stand structure characteristics of the experimental plots at the beginning of the study period.

	Site A—Brloško				**Site B—Bitoraj**			
	Plot 1	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 1**	**Plot 2**	**Plot 3**	**Plot 4**
Community	Silver fir forest with hard fern				Dinaric beech-fir forest			
Bedrock	Silicate				Limestone			
Soil type	Dystric cambisol				Calcocambisol			
Altitude, m a.s.l.	750	760	750	770	800	850	870	820
Slope, °	5	20	10	10	15	10	20	7
Exposure	Southwest				Southwest			
Average height of dominant trees, m	38.0	38.0	37.0	37.0	30.0	33.0	31.0	33.0
D (N ha^{-1})	90	96	92	95	398	354	375	380
B (m^2 ha^{-1})	33.9	49.1	35.7	40.1	25.4	26.4	27.2	27.5
V (m^3 ha^{-1})	469.3	595.9	475.0	512.0	283.0	293.0	312.0	310.3
Fr (%)	80	90	90	85	60	70	70	65
Cb (%)	10	5	10	10	30	30	25	25
Sy (%)	-	-	-	-	10	-	5	10
Sp (%)	10	5	-	5	-	-	-	-

Abbreviations: D—density; B—basal area; V—growing stock; Fr—silver fir; Cb—common beech; Sy—sycamore maple; Sp—common spruce.

Since the establishment of these plots in 1996, permanent silver fir monitoring was carried out over a period of 18 years. At the beginning of the monitoring period, all silver fir trees with over 10 cm diameter at breast height (DBH) (N = 273) were counted and DBH and height were measured. Annual stem growth (diameter increment, DI) was calculated using the following equation:

$$\mathrm{DI} = (\mathrm{DBH18} - \mathrm{DBH1})/\mathrm{T} \quad (1)$$

where DBH1 is the DBH of a tree in the first year, DBH18 is the DBH of the same tree in the 18th year, and T is the number of monitoring years (Table 1).

The social status of the trees was assigned to one of four groups: 1—dominant; 2—codominant; 3—subdominant; 4—suppressed [51]. Crown length was assigned to the following classes: >50% tree length; between 25 and 50% tree length; <25% tree length [6]. A laser height meter was used to measure the length of the illuminated portion of the crown, which is expressed as a percentage (%) relative to total crown length. Crown shape was classified into three categories: 1—symmetrical; 2—less symmetrical; 3—highly asymmetrical [52]. The shape of the top of the crown (stork's nest) was classified as one of the following: 0—none; 1—small; 2—moderate; 3—full stork's nest [7].

2.3. *Assessment of Crown Defoliation*

During the monitoring period, two trained observers conducted a visual assessment of the crown defoliation of silver fir each year in late July or early August with the aid of binoculars [31] and using a photo guide [53] as a reference. Defoliation of each tree was assessed from at least two positions at the distance of one tree height. After assessment, trees were classified into one of seven defoliation classes: class 0 (0–10%); class 1 (11–25%); class 2 (26–40%); class 3 (41–60%); class 4 (61–80%); class 5 (81–99%); and class 6 (100%, dead trees). Defoliation was assessed regardless of the cause of needle loss. All measured silver fir trees were also assessed for crown defoliation.

2.4. Climate Data

To analyze the relationship of climatic factors (air temperature (°C) and precipitation (mm) in the period from April to September) with silver fir defoliation, data from the Vrelo Ličanke meteorological station were used. This station is located in close proximity to both experimental plots (45°19′48″ N and 14°43′12″ E, altitude 750 m). Dry season water deficit (DSWD) was calculated as the difference between the monthly sum of precipitation and the sum of potential evapotranspiration [54] using the KlimaSoft 2.0 program. Potential evapotranspiration (PET; mm) was calculated using the method of Thornthwaite [55].

2.5. Statistical Analysis

For all analyzed variables, descriptive statistics were calculated. For all analyses, the significance level was set at 5%. Nonparametric correlation analysis (Spearman rank correlation) was used for confirming the relationship between tree defoliation class and climate and structural attributes. The defoliation class of silver fir trees at the experimental plots on sites A and B was correlated with the values of climatic factors of that year. The analyzed tree attributes were correlated with the mean crown defoliation class of each tree during the observation period. To analyze how long a tree remained in a given defoliation class, the repeated measure analysis of variance (RM ANOVA) and post hoc Tukey test was used. Since trees went through multiple defoliation classes, measurements in individual defoliation classes were not independent, and therefore, an RM ANOVA model was used:

$$\mathrm{Y_{ijk}} = \mu + \mathrm{S_i} + \mathrm{DC_j} + (\mathrm{S} \times \mathrm{DC})_{\mathrm{ij}} + \mathrm{ST_{k(i)}} + \mathrm{e_{ijk}} \tag{2}$$

where μ = overall mean; $\mathrm{S_i}$ = effect of site, where i = 1, 2; $\mathrm{DC_j}$ = effect of defoliation class, where j = 1, . . . , 5; $(\mathrm{S} \times \mathrm{DC})_{\mathrm{ij}}$ = effect of interaction between site i and defoliation class j; $\mathrm{ST_{k(i)}}$ = effect of $\mathrm{k^{th}}$ tree within $\mathrm{i^{th}}$ site; $\mathrm{e_{ijk}}$ = random error $\approx \mathrm{N}(0,\sigma^2)$.

As assumption of sphericity was not met (chi^2 = 715.33, df = 9, $p < 0.001$). The Greenhouse–Geisser epsilon correction was used for adjustment [56]. The percentage of overall tree survival during the monitoring period and the dynamics of tree transition between defoliation classes were assessed using the Kaplan–Meier estimation. Trees damaged by stem breakage were not included in the mortality calculation. The differences between sites A and B for overall survival and for the six defoliation classes were tested using the log-rank test [57]. For each defoliation class, the tree that entered that class in that year was coded as "complete". In the survival analysis, which included the Kaplan–Meier estimation, we defined an event that occurred (in our case, the entry of a tree into a defoliation class) as complete, and if not, it was censored. The statistical analysis of data was performed using the package Statistica 13.1 [58] and SAS 9.4 [56].

3. Results

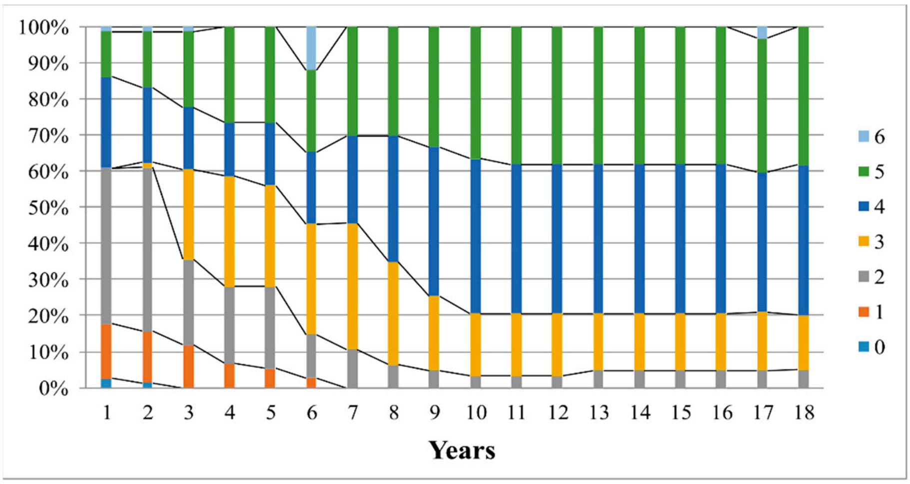
3.1. Crown Defoliation

Silver fir defoliation increased at both study sites during the study period. An increasing trend in the share of trees in defoliation classes 4 and 5 was recorded, while the proportion of healthy trees (classes 0 and 1) decreased (Figure 2).

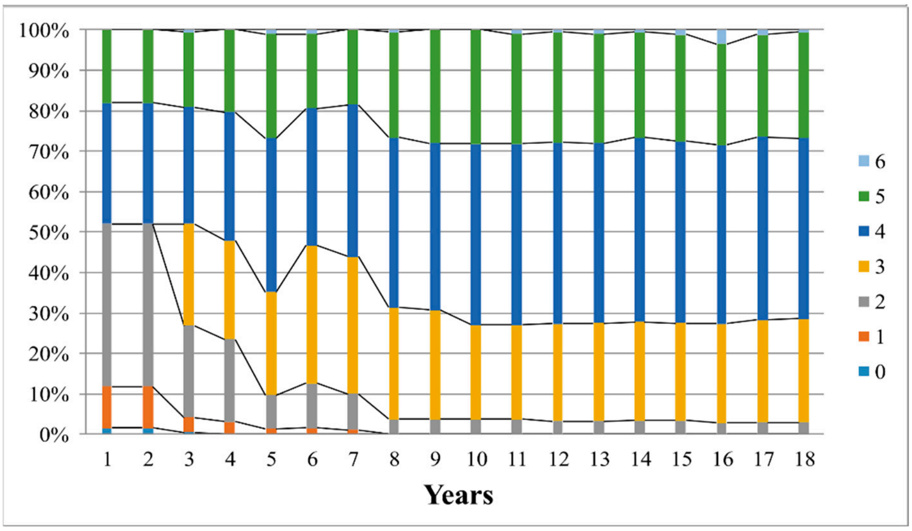
3.2. Climatic Factors

Table 2 shows the mean, minimum, and maximum values of climatic factors (precipitation and air temperature) and indices (dry season water deficit and potential evapotranspiration) for the 18-year monitoring period, as measured during the growing season from April to September.

According to the results of the Spearman correlation, the correlation coefficient between defoliation class and precipitation in the growing season was r = 0.14 (p = 0.409); for air temperature in the growing season, it was r = 0.44 (p = 0.005); and for potential evapotranspiration, it was r = 0.35 (p = 0.03). The only significant correlation between defoliation class and dry season water deficit was calculated for the month of June ($r = -0.55$, $p < 0.001$).



(**a**)



(**b**)

Figure 2. Silver fir defoliation at sites (**a**) (Brloško) and (**b**) (Bitoraj) according to defoliation classes (class 0, up to 10% defoliation; class 1, 11–25%; class 2, 26–40%; class 3, 41–60%; class 4, 61–80%; class 5, 81–99%; class 6: 100%—dead tree).

Table 2. Descriptive statistics of climatic factors and indices in the study area during the 18-year observation period.

Climatic Factor	Mean	Min–Max
Precipitation (mm)	953.66	585.60–1525.10
Air temperature (°C)	13.12	12.07–14.40
Dry season water deficit (mm)	76.03	−115.70–547.70
PET (mm)	494.13	468.50–529.10

3.3. *Stand Structure and Tree Attributes*

In the pure silver fir stand (site A), higher DBH values as well as higher increment rates, crown diameters, and crown illumination values were measured, while in the beech-fir stand (site B), the trees had longer crowns (Table 3).

Table 3. Descriptive statistics of structural attributes in the study sites. All silver fir trees over 10 cm (DBH) (N = 273) were measured.

Structural Attributes	**Sites**	
	A—Brloško	**B—Bitoraj**
	Mean (Min–Max)	
DBH (cm)	67.50 (18.45–114.75)	31.66 (11.55–61.70)
Growth increment (cm)	0.42 (0.02–1.11)	0.26 (0.002–0.93)
Crown diameter (m)	4.49 (1.70–7.75)	3.26 (1.40–6.54)
Crown length (%)	50.93 (37.50–75.00)	65.27 (12.50–75.00)
Crown illumination (%)	35.43 (0.00–80.00)	16.53 (0.00–60.00)

Table 4 shows the Spearman rank correlations of defoliation and structural attributes. The crown defoliation and structural attributes (DBH, crown illumination, social position of the tree, and the shape of the top of the crown) showed different correlations in the studied stands. In both stands, increased crown defoliation led to a decrease in radial increment. Additionally, a significant correlation was found between crown defoliation and crown illumination in both stands, but here, the effects varied: in stand A, defoliation increased, and in stand B, defoliation was reduced with increased crown illumination (Table 4).

Table 4. Spearman rank correlation between defoliation and structural attributes.

Structural Attributes	**Sites**	
	A—Brloško	**B—Bitoraj**
	Defoliation	
DBH (cm)	0.11	−0.45 *
Growth increment (cm)	−0.45 *	−0.53 *
Crown diameter (m)	−0.26 *	−0.59 *
Crown length (%)	−0.03	0.05
Crown shape	0.32 *	0.10
Crown illumination	0.29 *	−0.43 *
Social status of the tree	−0.14	0.40 *
Stork’s nest	0.34 *	−0.08

* Statistically significant at 5% level ($p < 0.05$).

3.4. Retention Time in a Given Defoliation Class, Transition Dynamics, and Tree Mortality

The results of the RM ANOVA show that there was a statistically significant difference in the retention time (time trees spent in a given defoliation class) at both sites (Table 5 and Figure 3). The greatest difference was found for defoliation class 4 (61–80%), which had an average retention time of five years in the pure fir stand and seven years in the beech-fir stand (Figure 3). When the sites and retention times in all defoliation classes were considered together, the post hoc Tukey test showed that all defoliation classes except for classes 3 and 5 were significantly different. The statistically significant interaction shows that the retention time in defoliation classes was not the same at both sites; trees at site B remained in classes 3 and 4 longer than those at site A did.

A certain level of silver fir crown regeneration was also observed. At site A, a temporary recovery (lower defoliation class than in the previous year) was recorded in 12.3% of trees during the whole monitoring period, as opposed to 23.7% of trees at site B (data not shown).

Regardless of the structural differences and the differences in site conditions between the study sites, there was a statistically significant difference between the sites only for the transition of trees into class 6 (100% defoliation—dead trees). Silver fir trees at site A transitioned to class 6 significantly earlier than trees at the beech-fir site B did (Figure 4 and Table 6). Additionally, the majority of trees entered class 6 from class 5 (64.28% at site

A, 72.72% at site B), while the remainder of the trees transitioned to class 6 directly from class 4.

Table 5. Results of repeated measure ANOVA for tree retention time as a dependent variable for both sites, crown defoliation class, and interaction between site and defoliation class. Significant effects are bolded.

Effect	df	MS	F	*p*
Site	**1**	**39.41**	**13.175**	**0.00034**
Error a	271	2.99		
Defoliation class	**4**	**984.23**	**35.765**	**<0.0001**
Site * defoliation class	**4**	**65.86**	**2.39**	**0.0489**
Error b	1084	27.52		

Note: * adjustment with Greenhouse–Geisser epsilon 0.6054.

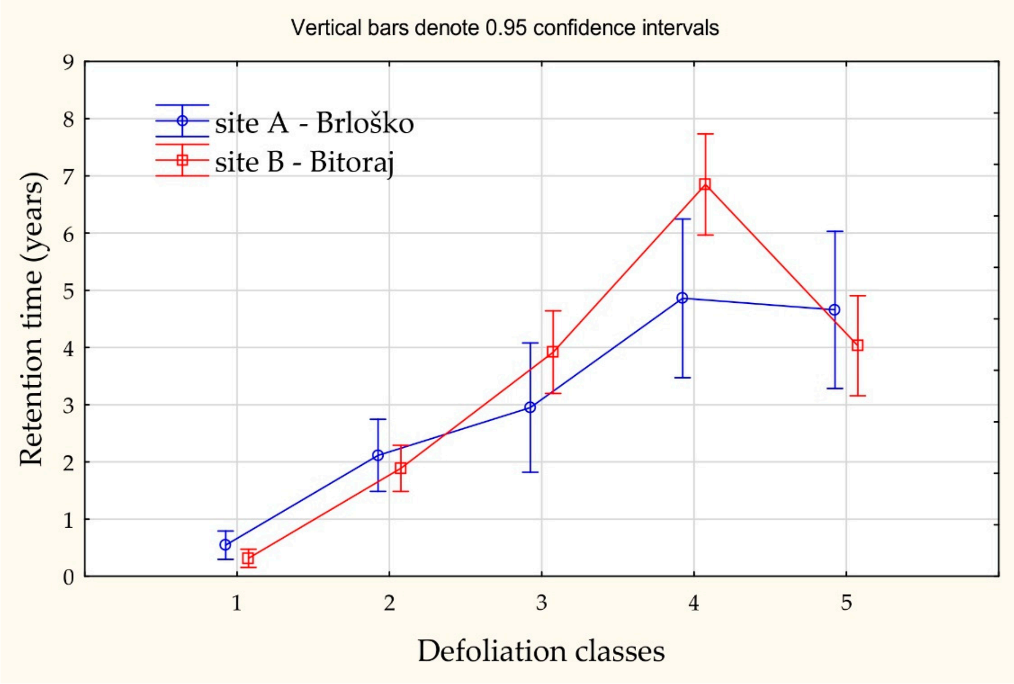
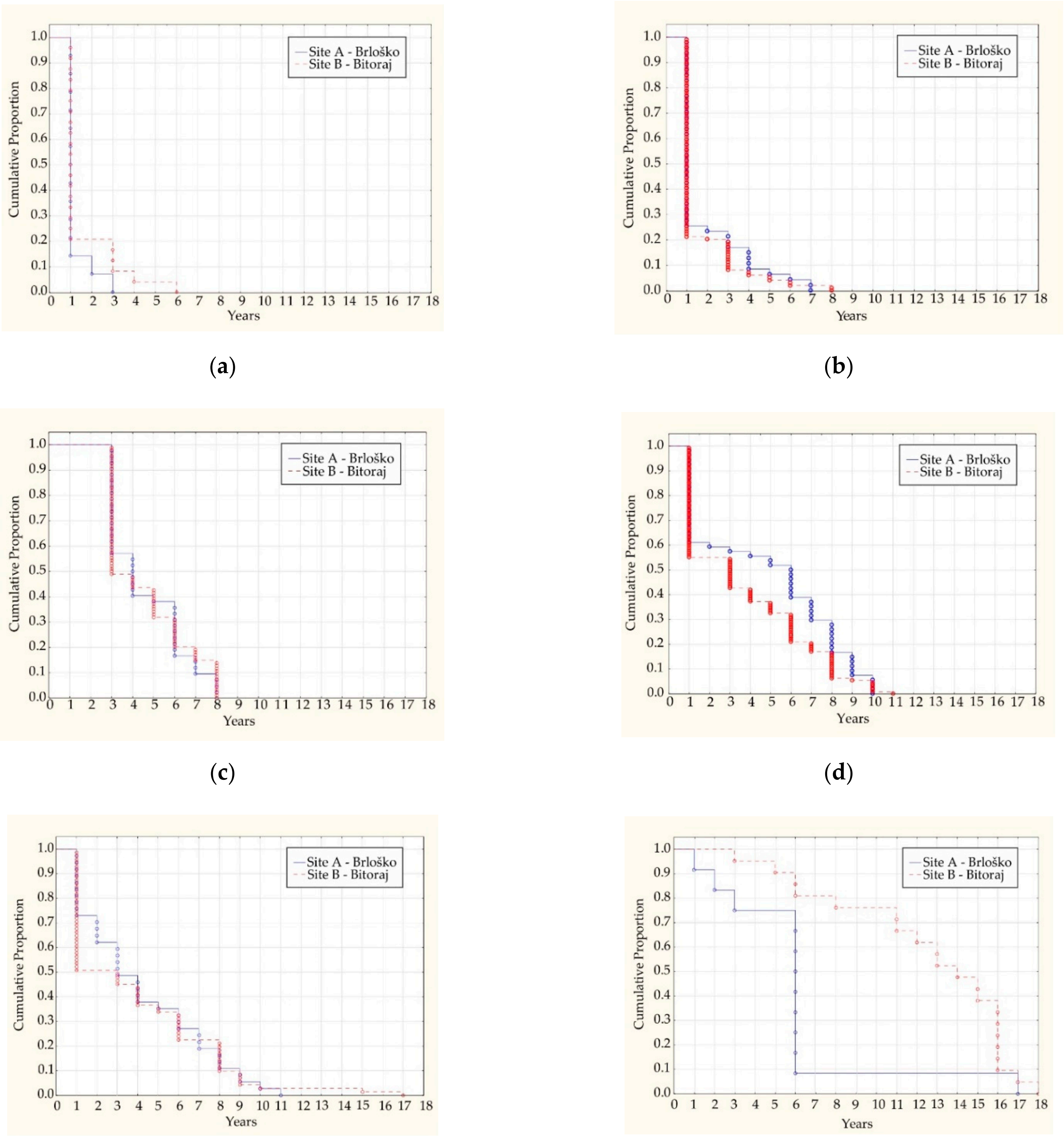


Figure 3. Retention time in a given defoliation class (in years) at research sites. Vertical bars denote 0.95 confidence intervals.

Table 6. Transition dynamics of trees between crown defoliation classes, and results of the log-rank test.

Defoliation Class	A—Brloško (N = 79)		B—Bitoraj (N = 194)		Log-Rank Test	
	N *	%	N *	%	Chi^2	*p*
1	14	17.72	24	12.37	1.477	0.2242
2	47	59.49	99	51.03	0.356	0.5508
3	42	53.16	94	48.45	0.050	0.8231
4	54	68.35	129	66.49	3.710	0.0541
5	37	46.84	71	36.63	0.005	0.9456
6	12	15.19	21	10.82	7.429	0.0064

Note: N * represents the number of trees that entered the given defoliation class during the 18-year observation period.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 4. Transition dynamics between defoliation classes as cumulative proportions of trees: (**a**) Transition to class 1; (**b**) Transition to class 2; (**c**) Transition to class 3; (**d**) Transition to class 4; (**e**) Transition to class 5; (**f**) Transition to class 6.

There were no significant differences in the mortality dynamics for sites A and B, even though the number of dead trees at the end of the monitoring period was different: 13 trees (16.46%) at site A compared to 21 (10.82%) trees at site B (log-rank test results: $chi^2 = 2.067$, $p = 0.0654$). Additionally, six trees at site A and five trees at site B suffered stem breakage due to strong winds.

Tree decline in the beech-fir stand (site B) was slower and more gradual in comparison with that in the pure fir stand (site A). At site A, tree mortality was most intense in the first

6 years and then stagnated until the 17th year of monitoring, while at site B, mortality was most present in the 16th monitoring year (Figure 5). At site A, the annual silver fir mortality was 0.94 N/ha, compared to 1.44 N/ha at site B. The maximum annual tree mortality was 8 trees/ha at site A and 6 trees/ha at site B.

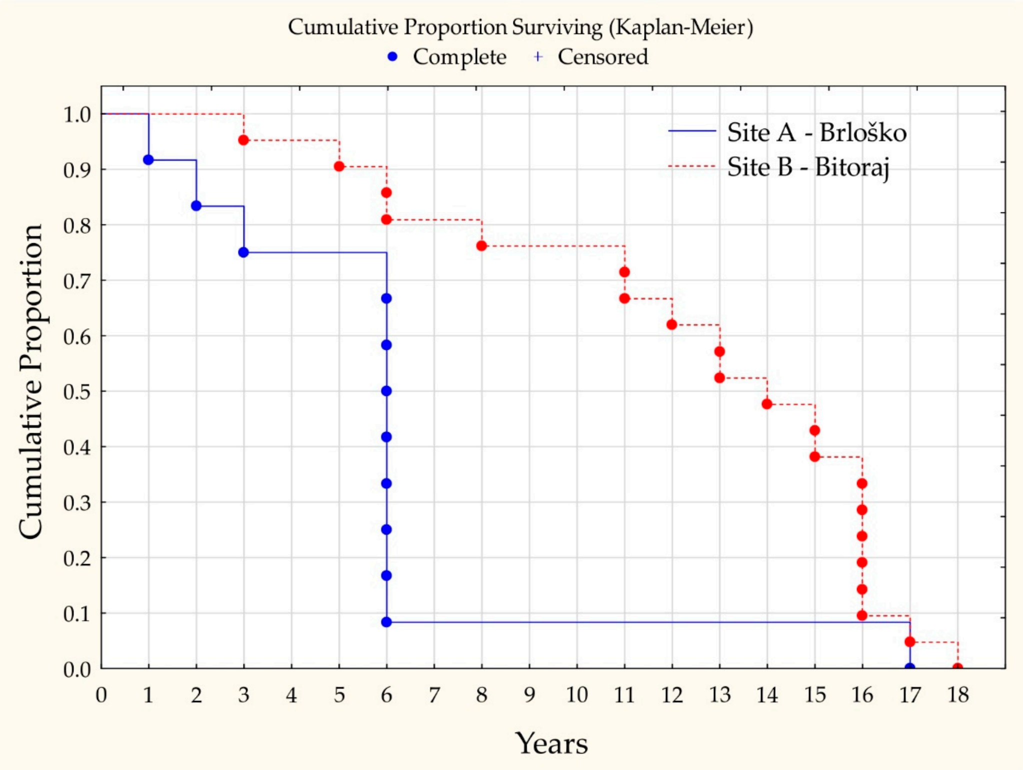


Figure 5. Annual mortality and cumulative proportion of surviving trees during 18 years at sites A (Brloško) and B (Bitoraj). Symbol "+" depicts mortality due to stem breakage.

4. Discussion

Continuous long-term monitoring allows for a better understanding of the tree decline processes in forest ecosystems. The percentage of trees in higher defoliation classes increased during the monitoring period at both experimental sites, which can be associated with their location near the southern edge of the silver fir distribution in Croatia, towards the warmer and dryer conditions of the Mediterranean climate. Poor vitality of silver fir has been observed in this area compared to the rest of the distribution range [22]. The percentage of significantly defoliated (>25% defoliation) silver fir trees in Croatia decreased constantly in the period 2003–2014 [59], although these numbers are difficult to compare directly. It is worth noting that, despite the declining trend, silver fir defoliation remained very high (62.4% of trees in 2014 were significantly defoliated). Although the trees at site A had better vitality in the first year of the study, their condition changed markedly over the 18-year period as the defoliation and mortality increased. This was particularly evident in comparison with site B, where the development of crown defoliation progressed more slowly. In contrast to the results of Bezak et al. [60], who observed no improvement in the crown condition of silver fir trees, a small portion of trees in this study experienced crown regeneration in certain years.

The results presented here suggest that increased defoliation of silver fir is associated with increasing air temperatures in the growing season, thus supporting the conclusions of Potočić et al. [30]. Increased amounts of potential evapotranspiration and reduced precipitation during the month of June also increased crown defoliation. Uhl et al. [61] consider silver fir to be drought-sensitive, while Vitasse et al. [62] concluded that silver fir has a high potential of success in western and central Europe despite the increasing air temperatures, as long as precipitation is sufficient. Dobrowolska et al. [9] and Čater and Levanič [63] found that unfavorable weather conditions, such as drought and increasing mean temperatures, reduce silver fir populations, while Tinner et al. [64] predicted that the future distribution range of silver fir will remain relatively unchanged, despite a warmer climate and increased air temperature levels, as long as mean precipitation remains above 800 mm per year. In this study, no significant effect of precipitation in the growing season was observed on crown defoliation. The amount of precipitation in the vegetation period ranged from 586 to 1525 mm, with a mean of 954 mm. However, under equal climatic conditions, the observed stands showed different responses in terms of development of defoliation and mortality. The roots of trees from the species *Abies* can be physiologically fused [65], and the formation of silver fir biogroups is more common on limestone substrates than on silicate substrates [66], which could have facilitated a better supply of nutrients and water to trees at site B.

Crown defoliation at both study sites showed a strong negative correlation with increment, which supports the findings of Erdle and MacLean [42], Bigler et al. [45], and Gazol et al. [67], who found differences in growth trends between trees with higher and lower degrees of defoliation.

Crown length is one of the most typical properties of fir trees [68]. The significant influence of crown length on tree vitality was described by Spathelf [5]. In this study, no correlation was found between crown length and crown defoliation. However, a significant correlation was found between crown defoliation and crown diameter, with smaller diameter crowns experiencing higher defoliation. A significant dependence of crown defoliation on crown illumination was also found. At site A, where trees had larger diameters and greater crown illumination, defoliation increased with increasing crown illumination. According to Prpić et al. [69], such crowns are more exposed to air pollution. Moreover, such trees had a pronounced stork’s nest crown, indicating older age and reduced vitality, in line with the findings of Oliva and Colinas [7].

Dobbertin and Brang [6] reported that crown defoliation correlated with the social position of trees and the degree of competition, which supports our results. Fir trees in the beech-fir stand (site B) were present at all layers, from dominant to suppressed, and a significantly positive correlation was found between defoliation class and the social position of trees, meaning that defoliation increased with reduced crown illumination. In contrast, fir tree crowns in the pure stand at site A were found only in the upper layer, and therefore, it was not possible to determine possible correlations of defoliation with tree social position.

Silver fir tree mortality over the 18-year monitoring period was 21.52% (average 1.2% per year) in the pure fir stand and 13.40% (0.74% per year) in the beech-fir stand. Bezak et al. [60] conducted a study in the beech-fir forests of the Western Dinarides on limestone substrate from 1969 to 1990 and found a mortality rate of 37% (1.23% per year). Senf et al. [70] reported that the average mortality in European temperate forests is 0.79% per year, with an increasing trend, while according to the data from the ICP Forests’ Technical Report, Forest Condition in Europe [71], total mortality of trees in 2019 was 0.9%.

The fourth (1999) and fifth (2000) years of the study were consecutive drought years; therefore, it can be assumed that this lasting climate stress further contributed to the increasing number of trees in defoliation class 6 in 2001.

The trees in the pure fir stand (site A) can be considered physiologically more mature, since this site had a significant number of trees with a prominent stork’s nest present. This would make the trees more susceptible to stress, and as a result, there was increased mortality at this site in comparison with site B in the study period. Similar conclusions were reached by Bigler et al. [45], who found that there was a greater risk of mortality for silver fir trees of greater height in higher defoliation classes. According to our results, the relationship between defoliation and mortality is not linear, but rather depends on a number of structural and site attributes that influence the onset of mortality. Therefore, it is not possible to determine how the vitality of a stand will evolve based on a single assessment. The results of this study confirm the necessity for permanent forest monitoring to ensure high-quality data, serving as the basis for more successful, up-to-date, adaptive forest management, including sanitary felling predictions.

5. Conclusions

This 18-year observational study in two types of silver fir stands examined the possible causes of crown defoliation in silver fir and its decline dynamics. Strong correlations were found between defoliation and structural attributes. More intense tree decline was found in the pure fir stands, which can be attributed to their presumed older age (trees with a stork nest), as deducted from the higher incidence of crown asymmetry coinciding with higher defoliation. Trees in the pure silver fir stand, which contained the most trees with a pronounced stork nest, died significantly earlier in comparison with the smaller silver fir trees in the mixed beech-fir stand. This suggests the possibility that adaptive management of fir stands could positively influence the structure of these stands and, thus, improve their health status.

Consistent with many previous studies, air temperature appears to have predominance over precipitation as a factor determining crown defoliation of silver fir, although the greatest transitions of trees to higher defoliation classes occurred after two consecutive years of drought.

Although this study is limited by design as it is a relatively local study, it was located at the southern edge of the silver fir distribution range, where climate change effects are expected earlier than in the rest of Europe. Despite the adaptations of local populations of silver fir, there is a legitimate risk that the thriving of silver fir at the southern edge of its distribution range will be hindered in the expected future climate conditions. In this region, increased silver fir defoliation and mortality can be expected, particularly in overmature stands facing prolonged drought stress.

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