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Influence of Tree Attributes on Silver Fir (*Abies alba* Mill.) Transitioning to Higher Defoliation Classes Determined by Logistic Regression

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Abstract: The age, size and morphology of trees, including crown dimensions, can influence crown defoliation. In Croatia, the selection management of silver fir (*Abies alba* Mill.) forests involves pure or mixed stands, either of which can be affected by various disturbances, resulting in unbalanced stand structures. The aim of this study was to estimate the probability of trees transitioning from one defoliation class to the next, examine the influence of tree attributes on that process and analyze the changes in survival over time. The study was conducted over a 18-year period (1990–2007) on two sites with contrasting stand structures: a uniform stand with a dominant share of silver fir (Site A) and an uneven-aged mixed beech–fir stand (Site B). Logistic regression was used to model tree transitions between defoliation classes. Uniform stand structure increased the likelihood of silver fir trees transitioning to a higher defoliation class, with limited dependence on the tree crown position. In contrast, suppressed and central trees in uneven-aged stands were more likely to transition to a higher defoliation due to greater competition between them. Diameter at breast height (DBH) was found to be a significant predictor of tree transition to higher defoliation classes, with a linear trend of increasing probability with increasing DBH. Crown position and crown length were also found to be significant predictors of changing defoliation class, with observed differences between sites occurring due to differences in stand structure. To ensure a balanced stand structure and enhance tree vitality, careful consideration of easily measurable tree elements such as DBH, crown length, and tree crown position is imperative when selecting trees for felling.

Keywords: crown condition; tree vitality; monitoring; uneven-aged stands; crown length; crown position

Citation: Jazbec, A.; Ugarković, D.; Ognjenović, M.; Vedriš, M. Influence of Tree Attributes on Silver Fir (*Abies alba* Mill.) Transitioning to Higher Defoliation Classes Determined by Logistic Regression. *Forests* **2023**, *14*, 1322. https://doi.org/10.3390/f14071322

Academic Editors: Andrej Bončina, Teresa Fidalgo Fonseca and Dalibor Ballian

Received: 1 April 2023
Revised: 11 June 2023
Accepted: 22 June 2023
Published: 28 June 2023

1. Introduction

Silver fir (*Abies alba* Mill.) (hereafter referred to as fir) is a vital tree species in the forest ecosystems of central and southern Europe as it plays an important ecological role as a keystone species in its native mountain ecosystems, providing habitat and food to a wide variety of wildlife, including birds, insects, and mammals [1]. Besides its ecological significance, fir is an important timber tree, and its wood is highly valued for its strength and durability, making it useful for multiple purposes. Historical emissions from industrial activity, primarily SO_2, have resulted in damage to fir forests and their decline [2,3]. However, with the reduction in industrial pollutant emissions, the species is now vulnerable to the impacts of climate change, such as drought and heatwaves, not to mention the increased frequency and intensity of extreme weather events [4–8]. These impacts are more pronounced on the edge of distribution. In Croatia, for example, it is predicted that the area of suitable habitat for fir may be reduced by up to 50% by the end of the century, depending on the severity of climate change [9].

The impact of climate change can be evaluated through tree vitality indicators such as crown defoliation, which is primarily assessed within the ICP Forests monitoring programme (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) [10]. Defoliation is defined as leaf loss in the assessable crown, as compared to a reference tree, and is observed regardless of the cause of foliage loss [11]. As a value, it can be determined cost-effectively and with relative speed in field surveys [12]. However, defoliation has been criticized due to the subjectivity of the assessment, as well as it being a nonspecific indicator affected by several biotic and abiotic factors [13,14]. Moreover, defoliation is only one aspect of tree vitality, and other indicators such as growth and stand structure may provide complementary information.

In Croatia, fir is distributed throughout the Dinaric Mountains, including the regions of Gorski Kotar and Lika, where it is associated with the introduction of the selection management practice [15,16]. The condition of selection forests in Croatia has been marked by disturbances in the selection structure due to a series of challenges [17], including the poor natural regeneration of fir, reductions to or increases in wood stock, reduced diameter increment, poor vitality, and the dieback of dominant trees [18,19]. A forest's stand structure can provide valuable information about the age, physiological maturity, and vitality of trees. The crown structure of trees within a canopy is among the most important aspects of stand structure as this is the location of vital physiological processes [20]. Crown length is a significant element of crown structure and constitutes one of the primary properties exerting influence on tree growth and development. Crown length undergoes dynamic change on the basis of tree age, tree position in the stand, and the management procedures performed in the stand.

In a fir stand managed with selection cuts, individual trees are carefully chosen for removal based on factors such as age, size, and health, with the goal of maintaining a diverse mix of tree ages and species within the stand [21]. This approach helps researchers to promote biodiversity, maintain soil, and water quality, and reduce the risk of catastrophic wildfires or disease outbreaks [22,23]. However, non-compliance with regulations and guidelines can lead to negative impacts on the forest ecosystem. For example, failure to implement appropriate management practices and adhere to regulations can result in the accumulation of wood stocks, increasing the risk of insect infestations and disease outbreaks [24,25]. In addition, a disturbed forest structure stemming from non-compliance with regulations can lead to disturbances in the relationships between forest components, such as increased competition and reduced natural regeneration [26–28]. Unbalanced stand structure can influence tree crown defoliation, particularly in coniferous species such as fir. Although limited research has been conducted on the influence of stand structure on tree defoliation, there have been various discussions regarding the correlation between different structural attributes and tree health. For example, Dobbertin and Brang [29] observed that the crown defoliation of various forest tree species, including fir, was related to the social position of the trees. Oliva and Colinas [18] reported that the presence of stork nests was among the symptoms of decline that coincided with defoliation in the fir decline process. Furthermore, Galiano et al. [30] discovered that an increase in Scots pine (*Pinus sylvestris* L.) defoliation was associated with both higher stand density and a larger diameter at breast height. Generally, research has shown that tree crown defoliation tends to be higher in stands with closed canopies and high stand densities, leading to greater competition for resources such as light and nutrients [12].

Fir forests cover approximately 180,000 ha in Croatia [31]. Considering the ecological and economic significance of Croatian forestry, there is a need to better understand threats to forest functioning and to determine the most appropriate measures to improve their management. In forestry practice, defoliation is one of the key criteria in allocating trees in regular and sanitation felling. There is a lack of studies examining the dynamics of trees transitioning to higher defoliation classes or of crown regeneration in relation to certain tree structure elements. Accordingly, the aims of this study were to estimate the probability of trees transitioning from one defoliation class to the next, examine the influence of tree attributes on that process by comparing two sites with contrasting stand structure, and to analyze the changes in tree defoliation and survival over an 18-year period (1990–2007).

2. Materials and Methods

2.1. Research Area and Forest Stands

The study was conducted in the Gorski Kotar region, a mountainous region of Croatia, in the distribution range of beech–fir and fir forests (Figure 1). These forests constitute the primary forest type in the montane vegetation belt [32]. According to the Köppen climate classification, the Gorski Kotar region has a moderately warm and rainy climate, without a dry period. The mean annual air temperature in the study area is 7.20 °C, while the yearly sum of precipitation is approximately 2000 mm [33]. The bedrock comprises limestone, dolomite, and sandstone of varying age, while the soil is dominated by brown soil on limestone and dolomite, in addition to acid brown soil. The relief of the study area is highly diverse, possessing many convex and concave forms. Two forest stands, each 1 ha in size, were selected for use in measurement and analysis (Table 1).

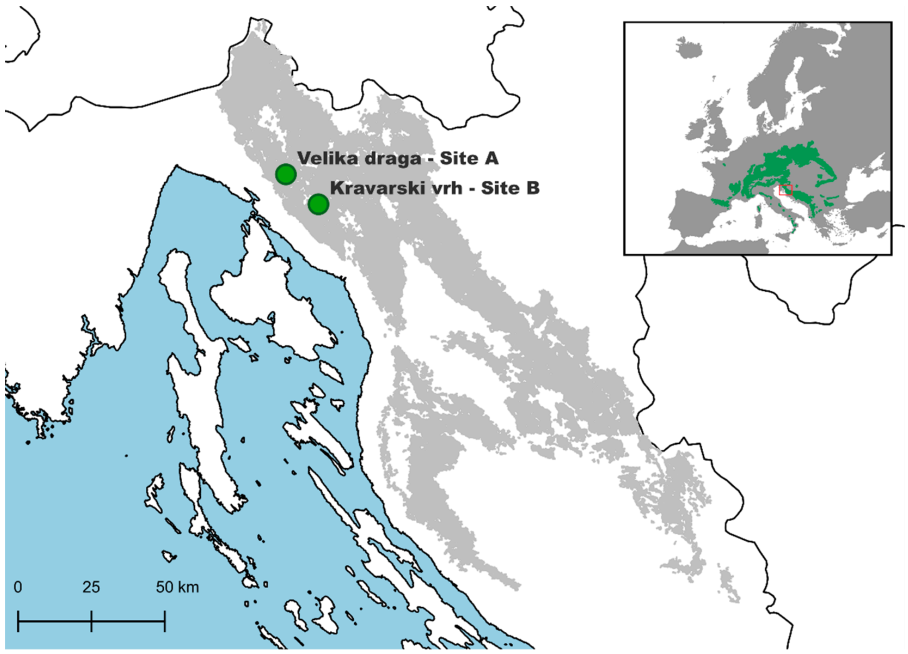

Figure 1. Location of forest stands (green dots) in research area and the distribution of silver fir forests in Croatia (grey polygon).

In Croatia, the most common fir forest communities include silver fir with hard fern (*Blechno-Abietetum*) and the Dinaric beech–fir forests (*Omphalodo-Fagetum*) of the western Dinarides [34]. Site A is a silver fir forest with hard fern and is a nearly pure stand. Such pure fir stands are rare and are the result of human influence [35]. This locality has soil rich in nutrients and with a relatively high moisture content due to the smaller watercourses flowing through this habitat. Site B is a mixed beech–fir forest of the western Dinarides. This forest type covers an area of about 140,000 ha in Croatia [34], with fir and European beech (*Fagus sylvatica* L.) serving as the dominant species, alongside a minor cohort of European ash (*Fraxinus excelsior* L.), sycamore maple (*Acer pseudoplatanus* L.) and Scots elm (*Ulmus glabra* Huds.) [36]. This site has less nutrient-rich soil and less soil moisture compared to the silver fir with hard fern forest located at Site A.

Table 1. Site description of analyzed forest stands. D—density; B—basal area; V—growing stock; Fr—silver fir; Cb—European beech; Cs—Norway spruce.

	Velika Draga—Site A	**Kravarski Vrh—Site B**
Coordinates	14°39′46.13″–45°20′10.46″	14°45′45.28″–45°16′18.78″
Community	Silver fir with hard fern	Dinaric beech–fir forest
Bedrock	Silicate	Limestone
Soil type	Acid brown soil	Brown soil
Altitude (m)	805	800–900
Slope (°)	5–20	10–45
Exposure	Southwest	Southwest
D (N ha^{-1})	332	540
B (m^2 ha^{-1})	33.94	27.84
V (m^3 ha^{-1})	469.37	271
Fr (%)	73	19
Cb (%)	22	69
Cs (%)	5	1

2.2. Assessment of Crown Defoliation and Measurement of Tree Structural Elements

Crown defoliation is defined as the loss of needles or leaves in the crown in comparison with reference trees and is observed regardless of the cause of loss of needles or leaves [11]. All fir trees with a diameter at breast height (DBH) greater than 10 cm were visually assessed for crown defoliation in comparison with the reference tree from the photo manual [37].

Monitoring assessments were performed once a year in July or August by two observers using binoculars with an accuracy of 5% [11]. After the defoliation assessment (Figure 2), fir trees were grouped into one of three defoliation classes: 1 (<25%) healthy, 2 (25%–60%) damaged, and 3 (>60%) severely damaged [38,39]. For dead trees, the cause of mortality was recorded. The cause of the mortality of fir trees was classified into three groups: C—complex causes (100% defoliation or 100% change in crown color caused by abiotic and/or biotic factors); W—mortality due to wind; and N—natural suppression, in which dead and hollow suppressed trees are found within the crown complex.

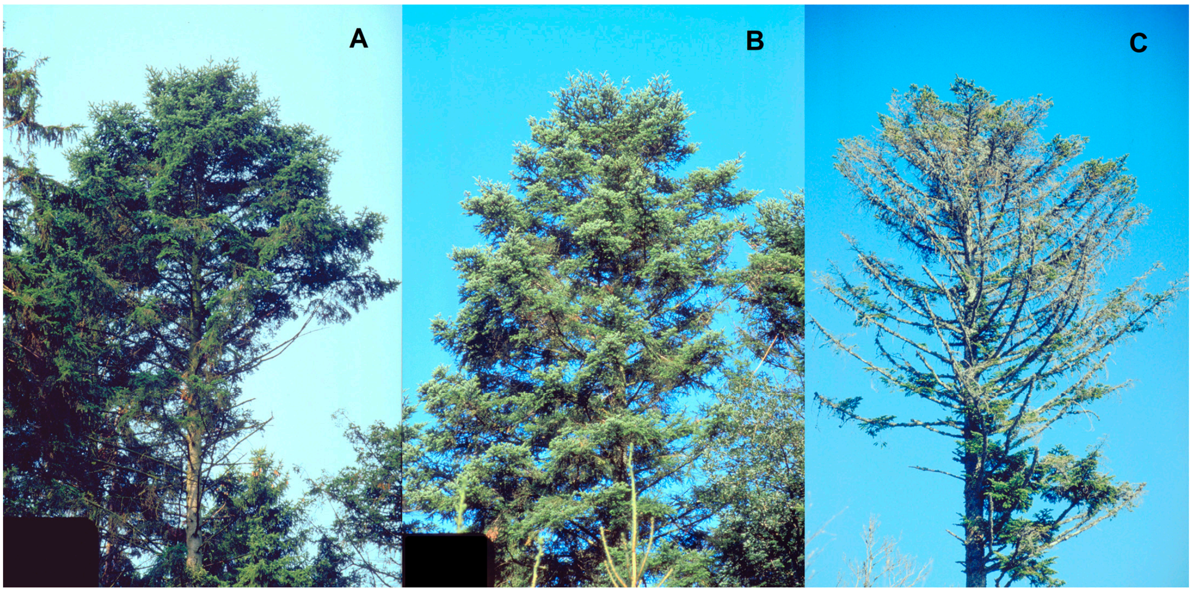

Figure 2. Examples of crown defoliation of silver fir in the research area. (**A**) 10% defoliation—Class 1. (**B**) 30% defoliation—Class 2. (**C**) 90% defoliation—Class 3 [11].

All fir trees with a DBH greater than 10 cm were measured twice to obtain the DBH at the start (DBH1990) of the monitoring period. A hypsometer was used to measure tree height and crown length. Crown length was measured from the tip of the crown to its base. The criterion used to define the crown base was the last green ring with a maximum of one dead branch from the tip of the tree [40]. Trees were grouped into one of three classes on the basis of crown length: >50% of tree height, between 25 and 50% of tree height, and <25% of tree height [29]. Trees on the plot were also grouped by their crown position into: (i) dominant—crowns extend above the general level of the canopy and receive full light from above and some light from the sides; (ii) codominant—crowns make up the general level of the canopy and they receive direct light from above, but little light from the sides; (iii) central—crowns occupy a subordinate position in the canopy and they receive some direct light from above; and (iv) suppressed trees—crowns are below the general level of the canopy and receive no direct light [29,41]. The crown length and crown position of trees did not change during the monitoring period. Dominant tree heights and DBH1990 were used to determine the theoretical (target) reverse-J diameter distributions (Figure 3) according to traditional uneven-aged forest management practices in Croatia [42,43]. During the years in which crown defoliation was monitored, no felling was performed in these silver fir stands.

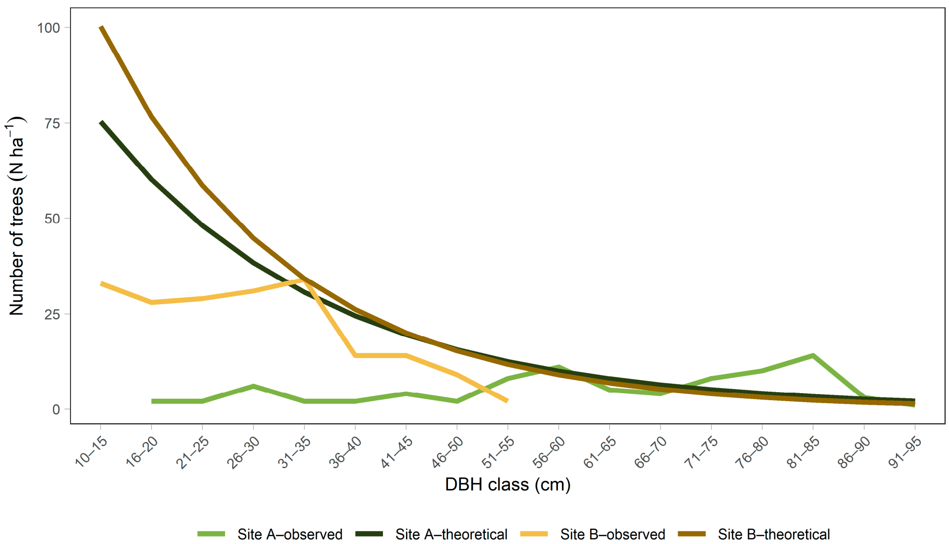

Figure 3. Theoretical and observed distribution of the number of silver fir trees (N/ha) by diameter classes in the analyzed forest stands.

2.3. Statistical Analysis

Descriptive statistics were determined for all analyzed variables. A significance level of 5% was considered statistically significant in all statistical analyses, unless otherwise stated. To test the differences in the dependent variable DBH1990 between locations (Site A and Site B), defoliation levels and their interaction, we applied a two-factor analysis of the variance (ANOVA). If an effect proved to be a statistically significant, Tukey post hoc test was used to determine the source of difference. The chi-square test was used to assess differences in survival rates between locations at the end of the monitoring period. To estimate the odds ratio of probability that trees are in higher than lower defoliation class, we used logistic regression with binary response, using defoliation classes (healthy—1, damaged—2, severely damaged—3) as the dependent variables, and DBH1990, crown length and crown position as independent variables. In this analysis, DBH1990 (cm) is used as a measure of physiological maturity. Since crown position is categorical (dominant, codominant, intermediate, suppressed), we used dummy variables where the dominant category was taken as the baseline. First, we evaluated models for each phase comparison of the dependent variable: level of defoliation class 2 vs. 1 (2/1) and 3 vs. 2 (3/2) for trees in 1990. After that, we used the Stuart–Maxwell test to determine whether the distribution of defoliation in 1990 and 2007 differed significantly for the same trees. We utilised logistic regression, i.e., the same logit model (Equations (1) and (2)), in order to estimate the probability that trees of defoliation level 1 or 2 in the year 1990 had changed into a higher defoliation class by 2007. Additionally, the goodness of fit was tested using the likelihood ratio (LR) and Hosmer–Lemeshow test [44].

$$\begin{aligned} \text{logit(p)} = \log(\text{p}/1-\text{p}) = \log(\text{odds ratio}) = \log(\text{OR}) = \beta 0 + \beta 1 \times \text{location} + \beta 2 \times \text{DBH1990} \\ + \beta 3 \times \text{crown length} + \beta 4 \times \text{codominant} + \beta 5 \times \text{central} + \beta 6 \times \text{suppressed}, \end{aligned} \quad (1)$$

$$\begin{aligned} \text{p} = 1/(1 + \exp(-\beta 0 - \beta 1 \times \text{location} - \beta 2 \times \text{DBH1990} - \beta 3 \times \text{crown length} \\ - \beta 4 \times \text{codominant} - \beta 5 \times \text{central} - \beta 6 \times \text{suppressed})), \end{aligned} \quad (2)$$

where p is the probability of being in the higher defoliation class, and $1 - \text{p}$ is the probability of being in the lower defoliation class.

All statistical analyses and graphical representations were performed in the statistical package SAS 9.4 [45].

3. Results

The difference in tree survival between the analyzed sites (Table 2) was statistically significant (chi-square = 5.72; $p = 0.017$).

Table 2. Descriptive statistics for DBH1990 (cm) and mortality of trees in period 1990–2007 by site and defoliation class.

Location	Defoliation Class in 1990	N	DBH1990 (cm)		Mortality of Trees in Period 1990–2007			
			Mean	Std Dev	Total	C	N	W
SITE A	1 healthy (<25%)	21	63.37	16.78	4	2	0	2
	2 damaged (25%–60%)	12	54.47	29.27	4	3	0	1
	3 severely damage (>60%)	48	71.86	19.79	13	11	0	2
SITE B	1 healthy (<25%)	26	26.16	9.79	2	0	0	2
	2 damaged (25%–60%)	48	37.67	10.86	9	6	2	1
	3 severely damage (>60%)	120	30.02	11.26	16	9	5	2

Number of trees by cause of mortality for each site: C—complex causes; W—mortality due to wind; N—natural suppression.

The results of ANOVA showed that there was a significant difference in DBH1990 between sites (Table 3). Fir trees at Site A (N = 60) possessed higher average DBH1990 (60.74 ± 10.67 cm) compared to the average DBH1990 (27.65 ± 10.59 cm) of trees at Site B (N = 168) (Table 1). There was also a statistically significant difference in DBH1990 with respect to defoliation classes assessed in 1990 (F = 8.39; $p = 0.0003$): 1 (N = 33) 33.49 ± 20.20 cm, 2 (N = 100) 41.08 ± 20.67 cm, 3 (N = 95) 32.39 ± 18.72 cm. The Tukey post hoc test showed that, regardless of location, there was a significant difference in DBH1990 with respect to defoliation class, whereby defoliation class 1 significantly differed from classes 2 and 3, while classes 2 and 3 did not differ significantly from each other. The significant interaction between site and defoliation class (F = 4.67, $p = 0.013$) indicated that DBH1990 did not behave equally by site or defoliation class.

Table 3. Results of ANOVA for DBH1990 between sites (A and B), defoliation assessed in 1990 and their interaction. Defoliation classes in parentheses are not statistically significantly different ($p = 0.05$).

Source	DF	F Value	Pr > F	Tukey Post Hoc Test
Site	1	195.34	<0.0001	(Site A) (Site B)
Defoliation	2	8.39	0.0003	(1) (2,3)
Defoliation × location	2	4.67	0.0103	

The logistic regression model showed no significant differences between sites (significance level of 5.1%) concerning the odds ratio of defoliation classes 1 to 2 (Table 4). At Site

B, the probability of fir trees being in defoliation class 2 was 4.497 times higher than being in class 1. The probability of being in defoliation class 3 at Site B was 77% higher than in level 2, although this result was not statistically significant ($p = 0.417$).

Table 4. Results of logistic regression for being in defoliation class 2 vs. 1 (model 1) and 3 vs. 2 (model 2) for the analyzed locations (Sites A and B), DBH1990, crown length, and crown position in 1990. LR: likelihood ratio; df: degrees of freedom; HL: Hosmer–Lemeshow; PE: parameter estimate; SE: standard error; OR: odds ratio.

	Model 1 **1(N = 33) 2 (N = 99) (2/1)** **−2LogL = 131.73** **LR = 16.73; df = 6; p = 0.010** **HL Test: chi^2 = 7.62; df = 8; p = 0.471**					**Model 2** **2(N = 99) 3 (N = 95) (3/2)** **−2LogL = 264.81** **LR = 18.09; df = 6; p = 0.006** **HL Test: chi^2 = 4.46; df = 8; p = 0.813**				
	PE	**SE**	**Wald Chi^2**	**p > chi^2**	**OR**	**PE**	**SE**	**Wald Chi^2**	**p > chi^2**	**OR**
Intercept	−3.37	1.75	3.71	0.054		−1.96	1.61	1.48	0.224	
Location	1.50	0.77	3.80	0.051	4.497	0.57	0.70	0.66	0.417	1.771
DBH1990	0.05	0.03	4.27	0.039	1.055	0.01	0.02	0.45	0.502	1.014
Crown length	0.02	0.01	1.92	0.166	1.016	<−0.01	<0.01	<0.01	0.962	1.000
Codominant *	1.24	0.70	3.41	0.076	3.463	1.24	0.49	6.42	0.012	3.440
Central *	0.34	0.81	0.18	0.673	1.410	1.73	0.67	6.62	0.010	5.656
Suppressed *	1.22	1.06	1.34	0.248	3.399	1.78	0.82	4.68	0.030	5.911

* Dominant crown position category was taken as the baseline.

DBH1990 was significant when estimating the probability of being in defoliation class 2 vs. class 1. With each 1 cm increase in DBH1990, the probability of being in defoliation class 2 vs. class 1 increased by 5.5%. There is a linear trend whereby the probability of being in defoliation class 2 vs. class 1 increases with increasing DBH1990 (Figure 4). DBH1990 did not prove to be significant in estimating the probability of being in defoliation class 3 vs. class 2, although the probability of deterioration within each crown position clearly increases with DBH1990 (Figure 5).

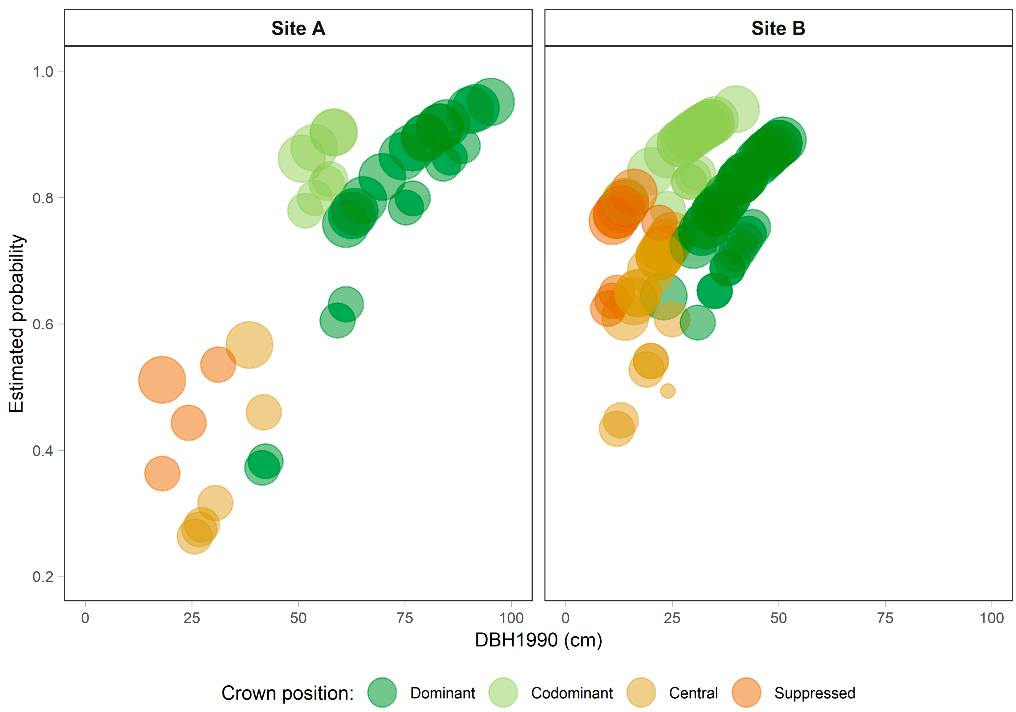

Figure 4. Estimated probability (Model 1) of being in defoliation class 2 vs. class 1 in 1990 according to the logistic regression model 1, including DBH1990, location and crown position. Bubble size represents crown length.

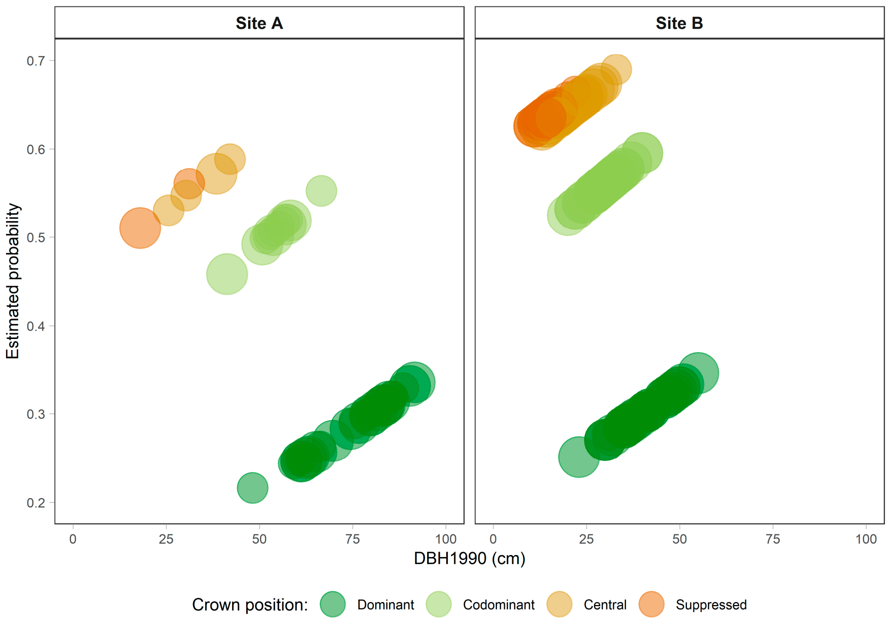

Figure 5. Estimated probability (Model 2) of being in defoliation class 3 vs. class 2 in 1990 according to logistic regression model 2, including DBH1990, location and crown position. Bubble size represents crown length.

Crown length did not prove to be a significant predictor in estimating the probability of being in a higher defoliation class (Table 4). On the other hand, crown position (canopy class) significantly affected the probability of trees belonging to class 3 vs. class 2. The dominant crown position was used as the baseline category, and those trees falling within it had the lowest probability of being in defoliation class 3 vs. class 2. The probability of being in class 3 increased with decreasing crown position (Figure 6).

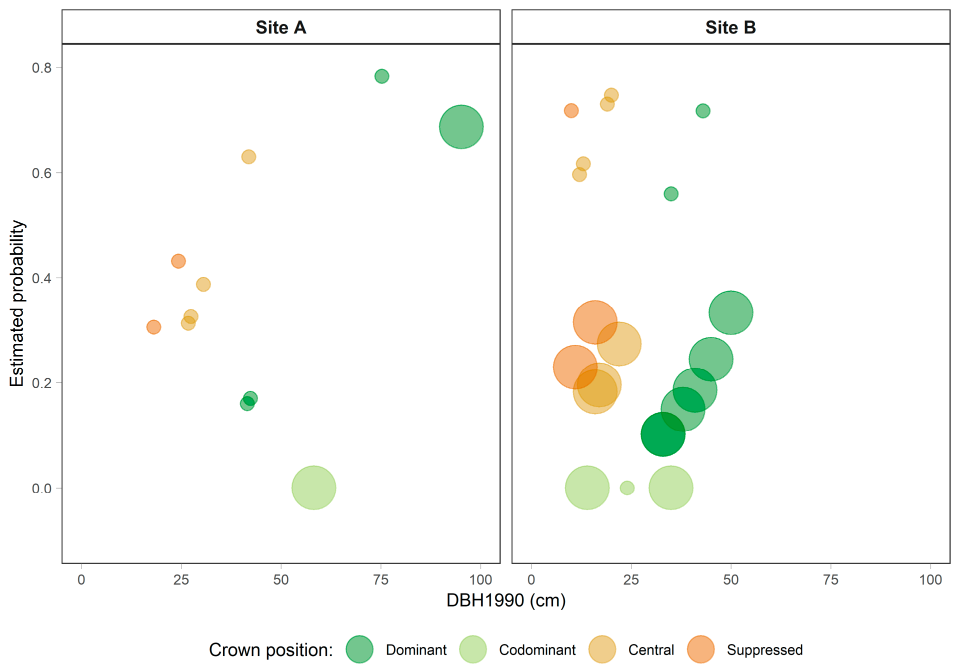

Figure 6. Estimated probability (Model 3) of being in defoliation class 3 vs. class 2 in 2007 for trees that were in defoliation class 1 in 1990 according to logistic regression model 3, including DBH1990, location and crown position. Bubble size represents crown length.

The Stuart–Maxwell test (chi-square = 40.50; df = 2; $p < 0.001$) did not establish marginal homogeneity in defoliation between 1990 and 2007. Therefore, the distribution of defoliation in 1990 differed significantly from defoliation in 2007 for the same trees (Table 5). During the investigated period, a deterioration in crown defoliation occurred in 100 (44.05%) trees: 21 (1→2); 12 (1→3); and 67 (2→3). For 120 (52.87%) trees, the condition remained unchanged: 32 (2→2); and 88 (3→3), while a recovery (3→2) was recorded for only 7 trees out of 95 (3.08%).

Table 5. Tree frequencies by defoliation classes in 1990 and 2007.

		Defoliation Class in 1990			
	Frequency Row Percent Column Percent	**1 Healthy (<25%)**	**2 Damaged (25%–60%)**	**3 Severely Damaged (>60%)**	**Total**
Defoliation Class in 2007	2 damaged (25%–60%)	21 35% 63.6%	32 53.3% 32.3%	7 11.7% 7.4%	60 100% 26.4%
	3 severely damaged (>60%)	12 7.2% 36.4%	67 40.1% 67.7%	88 52.7% 92.6%	167 100% 73.6%
	Total	33 14.5% 100%	99 43.6% 100%	95 41.9% 100%	227

We repeated logistic regression with the dichotomous dependent variables, defoliation classes 2 and 3, on trees showing deterioration in 2007. The model was the same as that used on the logistic models made for 1990 (Equations (1) and (2)). No significant differences were found between locations regardless of the defoliation class (1 or 2) recorded in 1990 (Table 6).

Table 6. Results of logistic regression for being in defoliation class 3 vs. class 2 (3/2) in 2007 for trees having a defoliation class 1 in 1990 (model 3) and defoliation class 2 in 1990 (model 4) based on the analyzed sites (A and B), DBH1990, crown length and crown position. LR: likelihood ratio; df: degrees of freedom; HL: Hosmer–Lemeshow; PE: parameter estimate; SE: standard error; OR: odds ratio.

	Model 3 **2 (N = 21) 3 (N = 12) (3/2)** **Defoliation 1990 = 1** **−2LogL = 3 2.49** **LR = 10.77; df = 6; *p* = 0.095** **HL Test: chi^2 = 4.62; df = 9; *p* = 0.866**					**Model 4** **2(N = 32) 3 (N = 67) (3/2)** **Defoliation 1990 = 2** **−2LogL = 113.21** **LR = 11.39; df = 6; *p* = 0.077** **HL Test: chi^2 = 4.61; df = 8; *p* = 0.841**				
	PE	**SE**	**Wald Chi^2**	***p* > chi^2**	**OR**	**PE**	**SE**	**Wald Chi^2**	***p* > chi^2**	**OR**
Intercept	−3.04	2.86	1.13	0.288		−2.16	2.39	0.81	0.367	
Location	2.46	1.45	2.86	0.091	11.696	−0.044	1.07	0.17	0.683	0.645
DBH1990	0.08	0.04	3.57	0.059	1.091	0.03	0.03	1.06	0.303	1.034
Crown length	−0.06	0.03	3.94	0.047	0.942	0.02	0.01	2.74	0.098	1.021
Codominant *	−10.42	213.9	<0.01	0.961	<0.001	0.66	0.66	1.00	0.316	1.934
Central *	2.16	1.59	1.75	0.174	8.645	1.41	0.99	2.02	0.155	4.101
Suppressed *	2.88	2.03	2.02	0.155	17.811	2.16	1.3	2.75	0.097	8.634

* Dominant crown position category was taken as the baseline.

Crown length proved to be a significant predictor for trees that were in defoliation level 1 in 1990 (Model 3). The higher the crown length, the lower the probability of being in defoliation class 3 vs. class 2, which was especially the case for trees at Site B (Figure 6).

The model for trees that were in class 2 in 1990 shows that Site B had a lower probability of deterioration than Site A (Figure 7). However, this result was not statistically significant. Although none of the independent variables in model 4 proved to be significant (Table 6), Figure 7 indicates that, regardless of canopy position and canopy height, all trees that were class 2 in 1990 had a high probability of being in a higher defoliation class (3) in 2007, regardless of DBH1990. At Site A, the probability of deterioration did not depend on crown position. However, as DBH increased so did the canopy position, i.e., the largest trees occupied a dominant position in the canopy layer. A similar process could be observed at Site B, except for the fact that the probability of being in class 3 vs. class 2 decreased with increasing DBH, whereas supressed trees had a higher probability of deterioration (Figure 7).

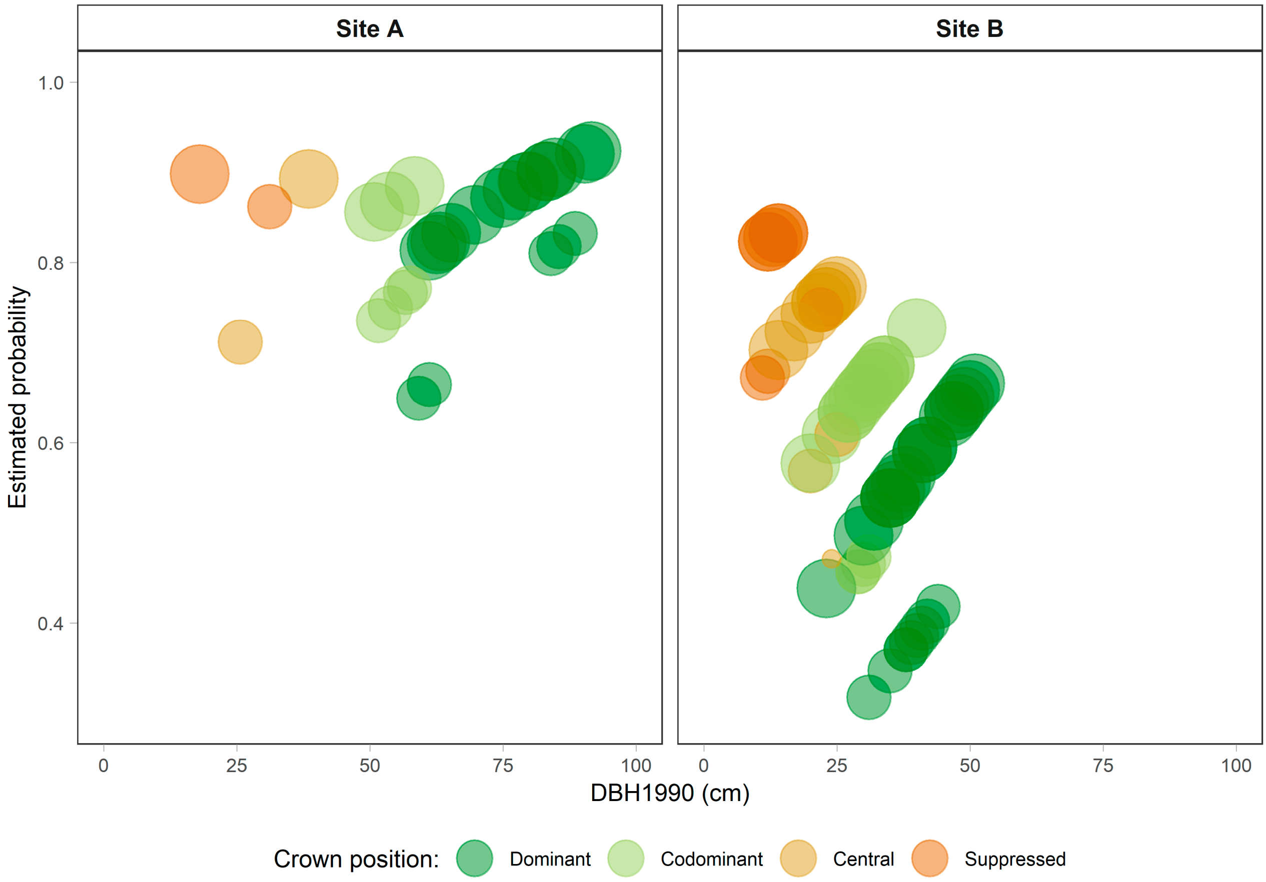

Figure 7. Estimated probability (Model 4) of being in defoliation class 3 vs. class 2 in 2007 for trees that were in defoliation class 2 in 1990, according to logistic regression model 4, including DBH1990, location and crown position. Bubble size represents crown length.

4. Discussion

The stand structure of fir forests can be highly heterogeneous depending on management practices and natural disturbances. The stand structure can range from uniform stands, where all trees are of similar size and age, to multilayered stands, where trees of different ages and heights coexist, to selection stand structures, where individual trees are selectively harvested to create a more diverse and complex forest structure [21]. Multilayer and selection structures are most typical stand variety [46]. The forest stands examined in this study are representative of fir stands in the Dinarides region of Croatia. Site B has reverse-J diameter distributions, while Site A has a depleted selection structure with a greater amount of wood per unit area and a higher proportion of trees with larger-diameters (Figure 3). In selection forests, these larger diameter trees often form the top layer [47], leading to a relatively uniform stand at Site A.

Throughout their long lifecycles, exceptionally tall trees are affected by various biotic and abiotic factors [42]. The top layer of trees in forest stands playing a crucial role in reducing air pollution by binding it to their leaves and needles [23]. At Site A, most trees occupy a dominant or codominant position, making them more susceptible to air pollution. Research has shown that taller trees with a larger DBH tend to exhibit a greater degree of crown damage [43], and that allometric features have an impact on the extent of crown defoliation.

The fir trees at Site A were taller and had larger DBH1990 values in comparison to those at Site B; accordingly, they displayed higher levels of defoliation. Site A possessed a considerable number of trees of concave crown shape, also known as a stork's nest [18]; these were used in combination with DBH to determine the maturity level of the trees. The linear trend of the increasing probability of being in defoliation class 2 vs. class 1 with increasing DBH1990 (Figure 1) may be explained by the age-related changes in crown defoliation described by Thomas et al. [38]. According to their study, age is one of the most significant factors influencing crown defoliation in fir trees. Additionally, Bezak et al. [48] found that younger trees tend to have higher vitality and identified physiological condition (maturity) as a factor in fir dieback.

Prpić and Seletković [49] conducted a 20-year monitoring program from 1971 to 1990; their research showed that 40% of the fir trees under consideration died due to a complex combination of factors causing complete crown defoliation. The causes of dieback were complex and included abiotic and/or biotic factors, which were the primary causes of dieback at both Site A and Site B. However, the present study found a lower percentage of dieback. Between 1990 and 2007, the stand at Site A experienced a 25.93% dieback rate, while Site B had a lower rate of 13.92% tree dieback.

When comparing mixed and pure forest stands, it is generally accepted that mixed stands exhibit greater resilience to biotic and abiotic disturbances [23]. In smaller, more fertile habitats on limestone substrates, fir trees tend to form biogroups of trees through the physiological fusion of tree roots, unlike those in fertile habitats on silicate substrates [50]. The formation of biogroups is a survival strategy that counteracts the negative effects of various stress factors and enhances stand stability. This could be a possible reason for the lower crown defoliation and reduced mortality rates of the fir trees at Site B.

Dobbertin et al. [29] determined that defoliation is correlated with the crown position of trees in the stand and the degree of competition among trees. In this study, all crown positions had significant effects on transitioning into the highest defoliation class (defoliation greater than 60%), making them candidates for sanitation felling [51]. Supressed trees were found to possess the highest probability of transitioning into the highest defoliation class, whereas dominant trees had the lowest probability. Fir is a sciophile species of forest tree that can survive for many years in shaded conditions in the lower layers of the forest canopy where light is mostly diffuse [1,28], although its grow still faces limitations.

The defoliation of fir can be reduced over the years or reversed once the impacts of stress have been reduced or the stress factor has ceased [49,52]. The defoliation of fir may reduce over time, provided that the stress factors are alleviated or eliminated [52]. Prpić and Seletković [49] found that 16% of fir trees showed crown recovery during long-term monitoring, which is higher than the 3.08% of trees observed doing so in their study. Since that study was conducted in the same study area, it appears that the negative stressors have a greater impact on fir trees. In this study, a high proportion of trees (36.4%) transitioned from defoliation class 1 to class 3, indicating the occurrence of severe crown damage on account of stress factors. Additionally, 40.1% of trees transitioned from defoliation class 2 into class 3 during the investigated period, marking an increase in the ratio of trees suitable for sanitation felling in accordance with Croatian forestry regulations [51].

Dominant fir trees in selection forests typically have a long crown, which generally accounts for one-half to two-thirds of the tree height [53,54]. Although crown length is an important biological trait of fir trees with significantly impacts on tree vitality [40], this was not significant for transitioning into a higher defoliation class at the beginning of the study period (Table 5). However, towards the end of the monitoring period, our results indicated that trees with higher crowns had a lower probability of being in defoliation class 3 vs. class 2 at Site B (Figure 6). The absence of felling or thinning during the monitoring period may have resulted in a reduction in crowns and subsequently reduced tree vitality, which is consistent with the findings of Spathelf [40] in regard to when forests are not thinned. Silvicultural treatments, such as tending and thinning, can be used to shape crown size or length and to influence the representation of trees in desired DBH classes [55].

Climate change is expected to have a significant impact on the distribution of fir trees in Europe [1]. According to a whole variety of studies, fir habitat suitability is projected to shift northward and towards higher elevations, with potential range reductions in southern Europe due to rising temperatures and changes in precipitation patterns [9,56,57]. Results of this study suggest that larger growing stock fir stands with degrees of higher competition exhibit decreased tree vitality, supporting earlier suggestions to enhance stand structure diversity and reduce growing stock as a means of mitigating the negative effects of climate change [58]. The degree of crown defoliation is dependent on the density of the crown canopy, with a thinner canopy resulting in higher defoliation, as demonstrated by Filipiak and Napierala-Filipiak [52]. In Croatia, fir is among the most affected and damaged conifer species, with intensive dieback recorded, especially in groups of trees, leading to the creation of openings in the crown canopy that further increase the crown defoliation of edge trees and destabilize the ecosystem as a whole [27].

The thorough comprehension of the transition of trees to higher defoliation classes calls for the consideration of additional factors, such as soil, climate, and stand structure. The limitations of this study, which should be addressed in future research, include the need to expand the sample size by incorporating a larger number of trees. By integrating these additional habitat factors and broadening the sample, future studies can provide a more comprehensive and detailed analysis of tree defoliation dynamics.

According to Dobbertin [12], central and supressed trees are exposed to higher stress levels due to greater competition in comparison with dominant and codominant trees. This is evident in our results, where supressed trees had a higher probability of transitioning from defoliation class 2 into class 3 at both time points, especially at Site B. Since Site A has a uniform stand structure, all trees are under uniform competition pressure, and this is reflected in their higher probability of transitioning into a higher defoliation class in the final year of monitoring (Figures 6 and 7). Therefore, it is important to apply silvicultural treatments to reduce competition among trees and to shape the crown to be as long as possible.

5. Conclusions

Regardless of stand structure, tree dieback was predominantly caused on both sites by the complete defoliation of the crown or by complex causes of dieback due to the unfavourable activity of abiotic and biotic factors. Only about 3% of trees were capable of regenerating their crown, which suggests a worsening impact of abiotic and biotic factors on fir vitality compared to what had been indicated by previous research. As well as having the highest tree mortality, fir trees within a uniform stand structure have a higher probability of transitioning into a higher defoliation class and, by the end of the monitoring period, transitioning did not depend on tree crown position. In contrast, suppressed and central trees in uneven-aged stands were more likely to transition to a higher defoliation due to greater competition. Additionally, shorter crown length proved to be detrimental for transitioning to a higher defoliation class. Considering that DBH can be used as a proxy for tree age, the results of this study confirm the negative effects of age on tree crown defoliation with an observed linear trend of increasing probability of transition with higher levels of DBH1990. Diameter at breast height and crown length are both easily measurable tree elements; combined together with the tree crown position, they can serve as criteria for selection cuts. The timely application of the appropriate silvicultural measures to stands, including intervention measures such as removing large-diameter trees, can contribute to tree vitality in selection stands.

Author Contributions: Conceptualization, A.J., D.U. and M.O.; methodology, A.J. and D.U.; formal analysis, A.J.; investigation, D.U.; resources, D.U.; data curation, A.J.; writing—original draft preparation, D.U. and A.J.; writing—review and editing, A.J., D.U., M.O. and M.V.; visualization, M.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to legal reasons.

Conflicts of Interest: The authors declare no conflict of interest.

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