forests

MDPI

Article

Private Forest Owner Characteristics Affect European Spruce Bark Beetle Management under an Extreme Weather Event and Host Tree Density

Maarten de Groot [1,*], Jurij Diaci [2], Kaja Kandare [3], Nike Krajnc [1], Rok Pisek [3], Špela Ščap [1], Darja Stare [1] and Nikica Ogris [1]

[1] Slovenian Forestry Institute, Večna pot 2, 1000 Ljubljana, Slovenia; maarten.degroot@gozdis.si (M.d.G.); nike.krajnc@gozdis.si (N.K.); spela.scap@gozdis.si (Š.Š.); darja.stare@gozdis.si (D.S.); nikica.ogris@gozdis.si (N.O.)
[2] Biotechnical Faculty, University of Ljubljana, Večna pot 83, 1000 Ljubljana, Slovenia; jurij.diaci@bf.uni-lj.si
[3] Slovenia Forest Service, Večna pot 2, 1000 Ljubljana, Slovenia; kaja.kandare@zgs.gov.si (K.K.); rok.pisek@zgs.gov.si (R.P.)
* Correspondence: maarten.degroot@gozdis.si

Citation: De Groot, M.; Diaci, J.; Kandare, K.; Krajnc, N.; Pisek, R.; Ščap, Š.; Stare, D.; and Ogris, N. Private Forest Owner Characteristics Affect European Spruce Bark Beetle Management under an Extreme Weather Event and Host Tree Density. *Forests* **2021**, *12*, 346. https://doi.org/10.3390/f12030346

Academic Editor: Maria Calviño-Cancela

Received: 16 December 2020
Accepted: 09 March 2021
Published: 15 March 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: In the last few decades, an increasing number and intensity of bark beetle outbreaks have plagued the forests of Europe and North America. Bark beetle management is directly related to forest owner characteristics, although this relationship is not well understood. The purpose of the study was to investigate the influence of forest owner characteristics on the amount and timing of sanitary felling under different disturbance regimes and quantities of Norway spruce. We combined different databases on sanitary felling, the timing of sanitary felling, and forest owner characteristics for Slovenia from 2014 to 2018 and analyzed the amount and timing of sanitary felling in relation to forest owner characteristics. We found that the timing in winter and the amount of sanitary felling were positively associated with the distance of the owner's residence to the forest parcel. Larger parcels were more affected by bark beetles but did not have later timing of cutting in the summer period as was hypothesized. The timing of sanitary felling decreased with property size, while with the probability of sanitary felling, the effect of property depended on the ice storm and the amount of spruce. The size of the settlement, the permanent address of the private owner, and timing of sanitary felling were positively associated but also depended on the amount of spruce. Gender and age did not have an important influence on the amount and timing of sanitary felling. Forest owners are an important factor in effective bark beetle management. This study highlights the private forest ownership characteristics that should be emphasized in order to fight bark beetle outbreaks in the event of large-scale disturbances. Governments should support forest owners who are at greater risk of bark beetle outbreaks and less efficient in managing outbreaks. Furthermore, landowner characteristics should be included when forecasting bark beetle outbreaks.

Keywords: close-to-nature management; sanitary felling; *Ips typographus*; forest pest management; forest owner characteristics

1. Introduction

In recent decades, forests in Europe have experienced severe pressure from invasive species and climate change and, as a consequence, more frequent large-scale outbreaks of forest pests [1–5]. Diebacks of oak and ash have wreaked havoc in forests, decreasing the fitness of trees or even killing them [6,7]. Climate change increases stress in important species such as beech, Norway spruce, and silver fir [1,8] and thus increases their vulnerability to forest pests [9]. Although climatic events cannot be avoided, sustainable forest management can possibly mitigate the consequences of catastrophic events [4,10–12].

Since around 28% of Europe's forests (including the European part of the Russian Federation) are privately owned [13], private forest owners are important stakeholders in forest management [14,15]. Typologies of private forest owners define their attitudes, values, beliefs, management objectives, and behavior, and this can influence the sustainability of forests [14,16,17], and it is, therefore, important to understand their influence on outbreaks of forest pests and their management against them.

In many countries, forest owners are obliged to follow the forest management plans prepared by the public forest service [18], but they also have a great influence on forest policy themselves. Through their behavior and management objectives, they have a great deal of control over stand structure [17,19]. This may mean that forest owners prefer monocultures or mixed stands, that they carry out large-scale clear-cutting leading to even-aged stands, or that they carry out selective felling leading to uneven-aged stands. Due to protection functions, tradition, and the overall small size of holdings, private forest owners in the Alpine region tend to prefer a more fine-grained forest stand matrix [20]. When forest pest outbreaks occur, it is often not in the forest owner's interest to allow trees to die or become less valuable due to forest pests, and they are therefore motivated to take appropriate measures [21]. If forest owners choose the most optimal measures for their forest, they thus ensure more profits and less monetary sacrifice [22]. It is interesting to note that there is little research on how forest owners actively manage the forest in the case of forest pest outbreaks and how forest owner typology affects success in dealing with outbreaks. This information would be very useful for guiding policy and encouraging landowners to improve forest pest management [23].

In order to test the influence of forest owners on pest management in forests, we used the European spruce bark beetle (*Ips typographus* L.) in Slovenia as a case study. *I. typographus* is one of the most destructive forest pests in Europe [24]. In recent decades, a combination of drought and windthrows or ice storms and increasing temperatures have resulted in an increasing number of large-scale outbreaks [4,5,8,12,25–28]. In addition, increasing temperatures increase the number of voltines per year, which increases the duration of outbreaks at higher altitudes [29] and decreases the vigor of Norway spruce [30], which makes it more susceptible to bark beetle outbreaks [24]. In Slovenia, bark beetles have had two large-scale outbreaks in the last two decades, one due to drought and one due to an ice storm [26]. It is therefore very important to find effective methods to mitigate the impacts of *I. typographus*.

Interestingly, studies have not focused on private forest owners as an important stakeholder in forest pest management, even though the responsibility for pest management normally falls on forest owners [31]. Furthermore, in Slovenia, close-to-nature management is practiced in a large part of the forest area, and guidelines for increasing tree diversity throughout the territory have been in place since the end of WWII [32]. Therefore, in order to improve this type of management, it would be useful to understand forest owner behavior. Additionally, in 2014, there was a large-scale ice storm that affected a large part of Slovenia [33]. Finally, Slovenia has a long tradition of measuring and monitoring all types of data on forests, forest management, and forest owners [34] and thus possesses unique databases that cannot be found in other parts of Europe. The situation in Slovenia thus provides a unique opportunity to study the association of increased large-scale disturbances on the efficiency of sanitary felling by forest landowners.

The aim of the study was to find possible associations between the effects of the ice storm, efficiency of bark beetle sanitary felling, and characteristics of forest owners. One of the important parameters is the timing of cutting because bark beetles emerge after a period of time and attack other trees. In Slovenia, this deadline for forest owners to cut infested trees is within 21 days of the initial discovery of the attack, otherwise, the felling will be conducted by the state at the cost of the forest owner, and in the winter period, cutting should be performed by the first emergence of bark beetles in the spring (Rules on Forest Protection (Official Gazette of the Republic of Slovenia, No. 114/09 and 31/16)). We investigated privately owned forests for bark beetle outbreaks and whether the cutting deadline was met in the summer and winter periods. We also analyzed the characteristics of forest owners and their properties regarding bark beetle outbreaks and the timing of cutting in the summer and winter periods. The comparison was performed between areas affected by the ice storm and not affected by the ice storm and areas with a different share of Norway spruce trees (hereafter spruce). We hypothesized that (1) a large distance between the forest parcel and the forest owner residence is more likely to be expressed in less active forest management and consequently in later cutting and more outbreaks; (2) co-ownership of the forest parcel can have a negative influence on forest management and therefore result in delays in the cutting of attacked trees; (3) large parcels have more spruce and therefore higher potential of sanitary felling and later timing of cutting; (4) forest owners with larger properties have more outbreaks (in absolute number of affected ha of forests) but are more active in forest management, more experienced, better equipped for forest operations, and better cooperate with forest contractors and therefore cut earlier; (5) forest owners living in urban areas are less active in forest management, which results in more outbreaks and later cutting; (6) older forest owners with more experience in forest management are more careful and notice an attack sooner and therefore cut earlier; and (7) the gender of forest owners has no specific influence on forest management activities and therefore also on the timing of sanitary felling.

2. Materials and Methods

2.1. Area Description

Slovenia is a country lying at the crossroads of the Alps, Dinaric mountains, pre-Mediterranean and pre-Pannonian regions [35]. The geology of a large part of Slovenia is limestone. More than half of Slovenia (58%) is covered by forests [34]. The Alpine forests of Slovenia were strongly influenced by the so-called German forestry school until WWII [32]. Many of the stands were changed into spruce monocultures, especially at lower altitudes [36], which consequently increased bark beetle outbreaks [12]. The most common tree species are beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) H.Karst.), and silver fir (*Abies alba* Mill.). Since the end of WWII, close-to-nature silviculture has become more influential and has been practiced all over Slovenia [32].

2.2. Databases

The dependent variable was the amount of sanitary felling of spruce due to bark beetles in the period from 2014 to 2018 per forest parcel in m^3 [37] (Table 1). The felling of every tree above 10 cm in d.b.h. in Slovenian forests must be legally approved by the Public Forestry Service. The felling is recorded in the Timber Database with the following data: location at the level of the forest sub-compartment and forest parcel, type of felling, tree species, number and volume of trees (m^3), deadline of felling, and the actual date of felling. There are nine general types of felling. Our study focused on two types of felling, i.e., sanitary felling and felling of weakened trees. Sanitary felling is further divided into 17 subtypes and felling of weakened trees into 11 subtypes. For the dependent variable, we used the amount of sanitary felling of spruce due to bark beetles.

The Timber Database was also the source of the three independent variables, i.e., whether the stand was affected by the ice storm in 2014, the mean number of days between the sanitary felling deadline and actual felling in the vegetation period (from March to September) and during winter (from October to February). The ice storm variable was binary (yes/no), in which "yes" only included the parcels that had sanitary felling and felling of weakened spruce due to the ice storm from 2014 to 2018 (Table 1).

The data on forest owners were obtained from the cadastral register [38] (Table 1). The original file contained 7,029,178 parcels. A spatial intersect of the cadastral register with the forest stand map [39] was performed to obtain forest parcels. There were 1,243,155 forest parcels. Each forest parcel can have many forest owners with different proprietorial shares. Only one forest owner with the highest proprietorial share was kept for further analysis.

The cadastral register was the source of the following forest owner attributes per forest parcel: gender, age, area of forest parcel, area of all forest parcels per forest owner, X and Y coordinates of forest parcel centroid, distance from forest parcel centroid to address of forest owner and the number of co-owners [40] (Table 1). Age and gender were taken from the owner with the highest ownership share in the database if there were co-owners. The distance from the forest parcel centroid to the permanent address of the forest owner was calculated by Euclidean distance.

Table 1. Description of the variables used in the models for the sanitary felling and timing of the sanitary felling.

Type of Variables	Variable Name	Description	Model Acronym
Dependent variables	Amount of sanitary felling	amount of sanitary felling of Norway spruce because of European spruce bark beetle per parcel from 2014–2018 (m^3)	Felling
	Days before/after deadline: summer	average difference in number of days between the deadline and the actual sanitary felling in the summer period (March-September)	Stiming
	Days before/after deadline: winter	average difference in number of days between the deadline and the actual sanitary felling in the winter period (October-February)	Wtiming
Independent variables	2014 ice storm	the ice storm damaged Norway spruce in the parcel 2014–2018 (yes/no)	IceStorm
	Gender of owner	gender of the forest owner, in the case with more owners, the gender of the largest owner was taken into account	Gender
	Age of owner	age of the forest owner, in the case with more owners, the age of the largest owner was taken into account	Age
	Parcel area	area of forest stands with Norway spruce in the parcel (m^2)	ParcelSize
	Area of all forest parcels per forest owner	area of all forest parcels of the forest owner	Property
	x/y coordinates of centroid	Centroid of the parcel (Gauss Krueger x and y coordinates)	XY
	Distance to owner residence	Euclidean distance from the owner residence to the forest parcel (m)	ParcelDist
	Number of co-owners	number of co-owners in the parcel	OwnersN
	Spruce coverage (low/high)	parcel with high and low amount of Norway spruce	Spruce
	Inhabitants in residence	number of inhabitants of the residence of the landowner	InhabitantsN
	Lag rate	auto-covariate in the model, which is an average of the outcome of neighboring values	Lag

The amount of spruce (m^3/ha) in the forest parcel was calculated from the forest stand map [39], which was spatially intersected with the cadastral register. One forest stand can cross several forest parcels. Wood stock is recorded by Slovenia Forest Service per forest stand. Therefore, the actual amount of spruce per forest parcel was calculated using the volume of spruce in the forest stand that was multiplied by the share of the forest stand in the forest parcel. In this calculation procedure, a uniform distribution of spruce across the forest stand was assumed. The amount of spruce per parcel was divided by the surface in hectares.

The number of inhabitants of the settlement of the permanent address of the forest owner was obtained from the eSTAT website (https://e2.stat.si/).

2.3. Data Management

For the analysis, we worked with three different datasets of parcels of private owners—the amount of sanitary felling, summer deadline, and winter deadline. For the sanitary felling dataset, only parcels with spruce were taken into account. For the summer deadline, records 22 days before the sanitary felling deadline were omitted because in Slovenia the deadline for sanitary felling is 21 days. For the winter deadline, all cases that were more or less than 61 days were omitted from the analysis as they reflect cases that were not recently found or were left because trees had already dried and were no longer proper brood material for bark beetles. From all of the datasets, 6000 different parcels were randomly selected because otherwise, the analysis would be too time-consuming. The parcels were equally and randomly chosen in areas that were not affected by the ice storm in 2014. Within the datasets, the amount of spruce was divided into high and low categories, with the median of the volume of spruce (m^3/ha) in Slovenia as the demarcation point. The datasets were divided into a training dataset (5000 parcels) and a validation dataset (1000 parcels). All unavailable data were omitted from the variables that were used in the analysis. The sanitary felling dataset included 3924 parcels, the summer deadline dataset included 3965 parcels, and the winter deadline dataset included 4207 parcels. The sanitary felling dataset included 1941 parcels for the high spruce category and 1983 parcels for the low spruce category. The summer deadline dataset included 4114 parcels for the high spruce category and 886 parcels for the low spruce category. The winter deadline dataset included 904 parcels for the low spruce category and 3303 parcels for the high spruce category.

2.4. Analysis

First, the data were inspected for normality, outliers, multicollinearity, and spatial autocorrelation [41]. The dependent variables were the absence and presence of the sanitary felling because of spruce bark beetles, amount of sanitary felling because of spruce bark beetles (above 0 m^3), days till the summer deadline and days till the winter deadline. The independent variables were the amount of spruce, whether the parcel was affected by the ice storm, gender of the forest owner, age of the forest owner, distance of the forest owner's residence to the forest parcel (hereafter distance to the forest parcel), number of owners, area of the parcel, the total area of the owned parcels, number of people living in the settlement where the forest owner lives and the amount of sanitary felling and interactions between the ice storm, amount of spruce, and the other separate variables. The amount of spruce was only used for the summer and winter deadline datasets. The independent variables distance to the forest parcel, number of owners, area of the parcel, the total area of the owned parcels, number of people living in the settlement where the forest owner lives, and amount of sanitary felling had many outliers and were also log +1 transformed. In all datasets, spatial autocorrelation was detected with global Moran's I statistics [42]. In the dataset with the sanitary felling, zero inflation was detected and therefore a two-step approach was used. First, a binomial regression was used and then a general linear model with a Gaussian error distribution was used. This distribution was used because there was zero inflation, and the variable was continuous. The spatial autocorrelation was included by use in spatial filtering and included Moran's eigenvector in the model [43]. For the amount of sanitary felling more than 0, the summertime deadline, and the wintertime deadline, the decision was either a spatial autoregressive lag or error model. The spatial autoregressive lag model and spatial error model are spatial models in which a spatial component is included. The spatial autoregressive lag model is modeled as a simultaneous equation in which one location partly depended on another location. The spatial error model considers space as a nuisance, which can affect the estimates and includes the space component in the error term [42]. On the basis of the coordinates, neighbor relationships were created. First, an ordinary least-square model was prepared, and diagnostics were used to determine the significance of the spatial lag and residual error. When one of them was significant, it was used in the model. When both were significant, robust diagnostics were used, and the one shown to be significant was used in the model [42]. For the sanitary felling dataset, a spatial error model was used (function errorsarlm()), and for the summer and winter deadline datasets, a spatial lag model was used (function lagsarlm()). Model selection was conducted with backward stepwise selection using the Akaike information criterion (AIC).

Data management, statistical analysis and visualization were performed in the program R [44] using the packages "Metrics" [45], "ggplot2" [46], "ggpubr" [47], "spdep" [48,49], "spatialreg" [48,49], "cplm" [50], and "adespatial" [51].

3. Results

The best model with sanitary felling included after stepwise backward selection of the variables, amount of spruce, ice storm, distance to the residence, parcel size, property size, and the age of the forest owner for the probability of an outbreak (Table 2, Figure 1). For the amount of sanitary felling, the amount of spruce, the age of the forest owner, distance, and size of the parcel were included in the model.

The amount of spruce was both for the probability (5.392, SE = 1.995) and amount of sanitary felling (–3.2, SE = 1.054) important, while the ice storm was only affecting the probability of sanitary felling (5.509, SE = 1.940)

For distance, there was a positive association found, which showed that with a larger distance from the residence place, the higher the probability (0.076, SE = 0.033) and the amount of sanitary felling (0.086, SE = 0.028).

For the parcel size, there was a positive association that shows that large parcels have a larger change for sanitary felling (0.294, SE = 0.052). There was also an interaction with an ice storm and an interaction with the amount of spruce. In areas with a low amount of spruce, there was no association between the amount of sanitary felling and parcel size (0.067, SE = 0.119), while in areas with a high amount of spruce, there was in larger parcels much larger sanitary felling (0.432, SE = 0.126).

For the property size, there was an interaction found between property size and amount of spruce and also with the ice storm regarding the chance of sanitary felling. In areas with a low amount of spruce, there was no association between the probability of sanitary felling and property size (0.231, SE = 0.231), while with a high amount of spruce (–0.3, SE = 0.177) and areas affected with ice storm (–0.326, SE = 0.173)), larger properties had a weaker association with the probability of sanitary felling. In areas with the ice storm, the probability of sanitary felling was much higher in larger properties with a high amount of spruce compared to areas with the ice storm (0.532, SE = 0.21).

For the age of the forest owner, there was a weaker association between the owner's age and the probability of sanitary felling (0.005, SE = 0.003) and the amount of sanitary felling (0.005, SE = 0.003).

For the binomial model, there was no spatial autocorrelation found (Moran's I = 0.05, $p = 0.172$). The Nagelkerke R^2 for the binomial model was 0.43. For the amount of sanitary felling, there was still spatial autocorrelation found (lambda = 0.326, $p < 0.001$). The model was much better when including spatial autocorrelation structure (AIC: 2486.2) than without (AIC: 2538.3). The RSME from the validation dataset was 145.56 and from the training, the dataset was 170.54. The Nagelkerke R^2 was 0.26.

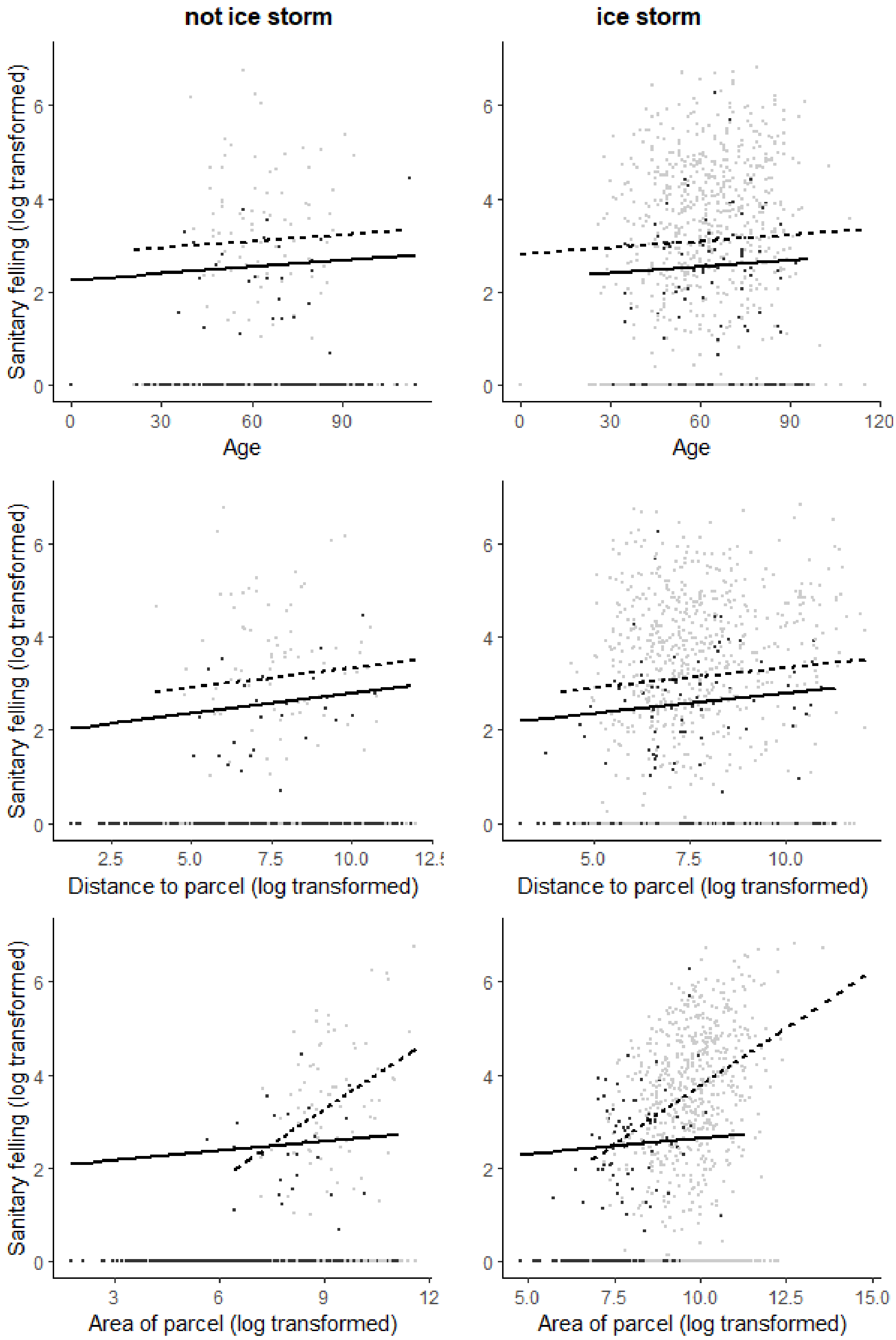

Figure 1. Association of the different characteristics of the privately owned parcels with the presence of the ice storm and the amount of spruce with the amount of sanitary felling (m^3). The grey dots and the black dashed line show a high amount of spruce and the black solid line and black dots show a low amount of spruce. Prediction lines are only shown for the spatial error model in which sanitary felling > 0.

Table 2. Statistics of the binomial and spatial error models for sanitary felling. Variables, estimates, standard error, z value, and *p* values are shown. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, [1] Moran eigenvectors used in the model are not shown.

Model type	Variables	Estimate	SE	z	*p*	
Binomial model[1]	(Intercept)	-10.034	1.662	-6.038	0.000	***
	Spruce-high	5.392	1.995	2.703	0.007	**
	IceStorm-True	5.509	1.940	2.840	0.005	**
	Age	0.005	0.003	1.696	0.090	.
	log(1 + ParcelDist)	0.076	0.033	2.328	0.020	*
	log(1 + ParcelSize)	0.294	0.052	5.660	0.000	***
	log(1 + Property)	0.231	0.140	1.648	0.099	.
	Spruce-high * IceStorm-True	–6.811	2.358	-2.888	0.004	**
	Spruce-high * log(1 + Property)	–0.300	0.177	-1.693	0.090	.
	IceStorm-True * log(1 + Property)	–0.326	0.173	-1.879	0.060	.
	Spruce-high * IceStorm-True * log(1 + Property)	0.532	0.210	2.532	0.011	*
Spatial error model	(Intercept)	1.066	1.003	1.062	0.288	
	Spruce-high	–3.200	1.054	-3.035	0.002	**
	Age	0.005	0.003	1.687	0.092	.
	log(1 + ParcelDist)	0.086	0.028	3.028	0.002	**
	log(1 + ParcelSize)	0.067	0.119	0.562	0.574	
	Spruce-high * log(1 + ParcelSize)	0.432	0.126	3.427	0.001	***

3.1. Summer Deadlines

In general, the estimates showed that finishing the sanitary felling in the summertime was on average later than the time set by the forester (Figure 2, Table 3).

There was no difference in finishing the sanitary felling in parcels with a low or high amount of spruce (3.86, SE = 2.24); however, in areas affected by the ice storm, the finishing of the sanitary felling was later (9.43, SE = 4.10).

For the number of owners, the results showed that the parcels with more owners had a later response regarding sanitary felling (1.71, SE = 0.73).

For the size of the parcel, there was an interaction between parcel size and the presence of the ice storm. In areas where there was no ice storm, larger parcels had a later sanitary felling compared to smaller parcels (0.59, SE = 0.32), while in areas with ice storm, there was faster timing of sanitary felling in larger parcels than in smaller ones (–0.99, SE = 0.43).

For the property size, the sanitary felling was earlier in larger properties than in smaller properties (–0.83, SE = 0.22).

The number of inhabitants of the settlements where the owner lives and the amount of sanitary felling interacted with the amount of spruce. For the low amount of spruce, sanitary felling was earlier when the forest owner came from places with fewer inhabitants (0.58, SE = 0.25); for the high amount of spruce, the timing was earlier when the settlement where the forest owner lives had more inhabitants (–0.58, SE = 0.28), which led to the conclusion that there is no difference in timing between settlements with less and more inhabitants.

When there was much sanitary felling, the timing of finishing the sanitary felling was later (1.16, SE = 0.23).

At 0.05, the Nagelkerke R^2 was low. The RMSE decreased from 17.1 in the training set to 16.7 when used in the validation set. There was still spatial autocorrelation observed when using the spatial lag test (test value = 46.492, $p < 0.001$). Including the spatial terms improved the model (AIC spatial lag model: 33590; AIC lm: 33726).

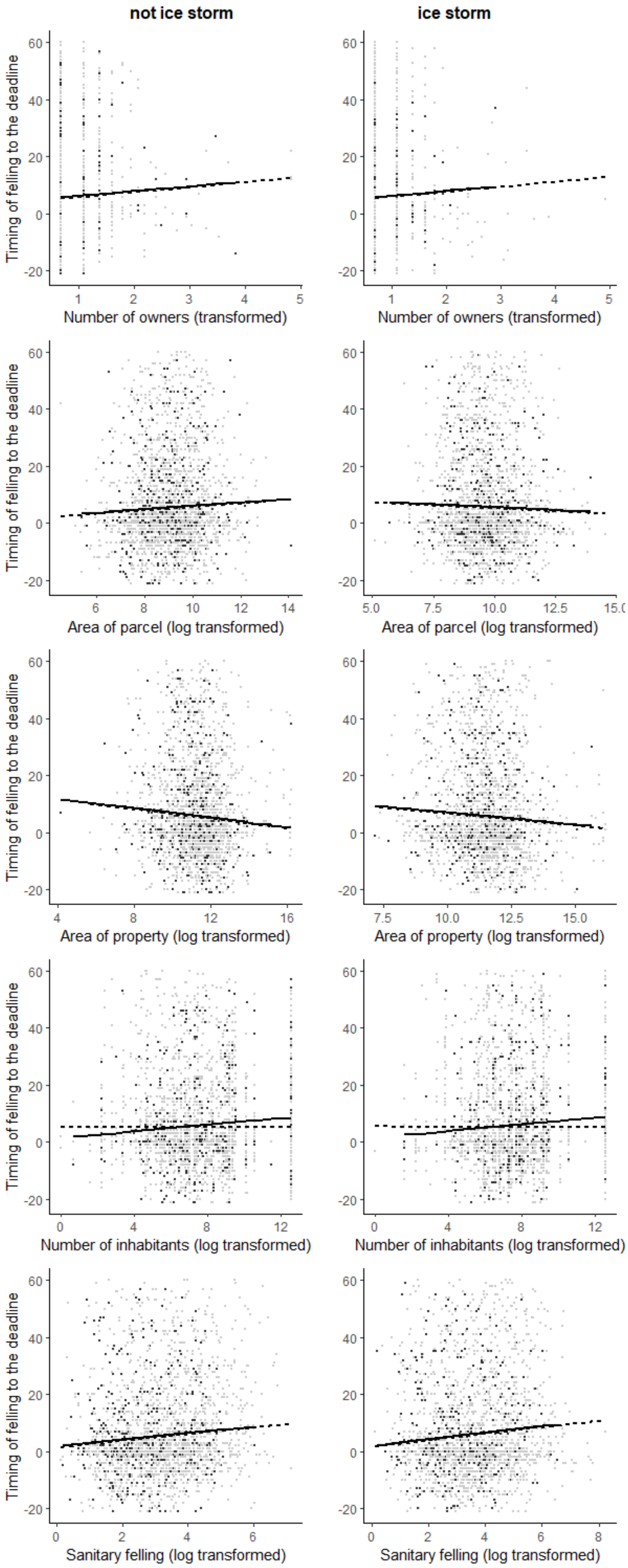

Figure 2. Associations of the different characteristics of the privately owned parcels with the presence of the ice storm and the amount of spruce with the timing of felling in the summer period. The grey dots and the black dashed line show a high amount of spruce and the black solid line and black dots show a low amount of spruce.

Table 3. Model statistics of the spatial lag model of the timing of sanitary felling in summer and winter. Variables, estimates, standard error, z value, and *p* values are shown. Adapted direct and indirect impact values of the models are included. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Direct impact values show the direct feedback of neighboring parcels in the dataset to the particular parcel. The indirect impact shows the changes in all observations also called spatial spillover. The total impact is the sum of the indirect and direct impact [52].

Dependent Variable	Variables	Estimate	SE	*p*	Direct Impact	Indirect Impact	Total Impact
Summer timing	(Intercept)	0.29	3.78	0.94			
	Spruce-high	3.86	2.24	0.09	3.91	1.19	5.10
	IceStorm-True	9.43	4.10	0.02 *	9.55	2.90	12.45
	log(1 + OwnersN)	1.71	0.73	0.02 *	1.73	0.53	2.26
	log(1 + ParcelSize)	0.59	0.32	0.06	0.60	0.18	0.78
	log(1 + Property)	−0.83	0.22	0.00 ***	−0.84	−0.25	−1.09
	log(1 + inhabitantsN)	0.58	0.25	0.02 *	0.59	0.18	0.76
	log(1 + Felling)	1.16	0.23	0.00 ***	1.18	0.36	1.53
	Spruce-high * log(1 + inhabitantsN)	−0.58	0.28	0.04 *	−0.59	−0.18	−0.77
	IceStorm-True * log(1 + ParcelSize)	−0.99	0.43	0.02 *	−1.00	−0.31	−1.31
Winter timing	(Intercept)	17.19	10.45	0.10			
	Amount of spruce-high	−21.48	11.49	0.06	−21.94	−9.09	−31.03
	IceStorm-True	−24.03	15.77	0.13	−24.55	−10.17	−34.71
	log(1 + ParcelDist)	0.36	0.77	0.64	0.37	0.15	0.52
	log(1 + OwnersN)	1.62	1.11	0.14	1.66	0.69	2.35
	log(1 + ParcelSize)	−1.28	0.94	0.17	−1.31	−0.54	−1.85
	log(1 + Property)	−0.61	0.31	0.05 *	−0.62	−0.26	−0.88
	log(1 + Felling)	−0.92	0.31	0.00 **	−0.94	−0.39	−1.33
	Spruce-high * IceStorm-True	51.41	17.59	0.00 **	52.51	21.76	74.26
	Spruce-high * log(1 + ParcelDist)	0.76	0.87	0.38	0.77	0.32	1.09
	Spruce-high * log(1 + ParcelSize)	1.8	1.04	0.08	1.84	0.76	2.61
	IceStorm-True * log(1 + ParcelDist)	1.66	1.11	0.14	1.69	0.7	2.4
	IceStorm-True * log(1 + ParcelSize)	1.13	1.38	0.41	1.16	0.48	1.64
	Spruce-high * Ice storm-True * log(1 + ParcelDist)	−2.69	1.25	0.03 *	−2.75	−1.14	−3.89
	Spruce-high * IceStorm-True * log(1 + ParcelSize)	−3.24	1.53	0.03 *	−3.31	−1.37	−4.68

3.2. Winter Deadlines

The average finishing time of sanitary felling in the winter was also later than the deadline (Figure 3, Table 3).

There were no differences observed in the timing of finishing the sanitary felling between areas with low and high amounts of spruce (–21.48, SE = 11.49) and areas affected and not affected by the ice storm (–24.03, SE = 15.77).

In general, there was no association between the finishing of the sanitary felling and the distance to the parcel. There was also no general difference in the association between finishing the sanitary felling and the distance to the parcel between areas with a low or high amount of spruce or in areas with or without ice storm. However, distance to the parcel had a three-way interaction with the presence of the ice storm and the amount of spruce. In areas without the ice storm, there was no association between distance to the parcel and timing when there was a low amount of spruce (0.36, SE = 0.77), but in areas with a high amount of spruce, for forest owners living further away, there was no difference compared to the lower amount of spruce (0.76, SE = 0.87). In areas with the ice storm, for forest owners living further away, there is a non-significant association with the sanitary felling in areas with a low amount of spruce compared to areas without ice storm (1.66, SE = 1.11), but in areas with a high amount of spruce, the larger distance to the parcel had a shorter timing compared to the low amount of spruce in areas with ice storm (–2.69, SE = 1.25).

For the number of forest co-owners, the timing of the sanitary felling was not significantly associated with more forest owners (1.62, SE = 1.11).

There was no significant association between finishing the sanitary felling and the area of the parcel. There was also no significant difference in the association between finishing the sanitary felling and the area to the parcel between areas with a low or high amount of spruce or in areas with or without ice storm. However, there was a three-way interaction found with the presence of the ice storm and the amount of spruce and parcel size in relation to parcel size. For the areas without the ice storm, larger parcels had earlier sanitary felling with the low amount of spruce (–1.28, SE = 0.94), while with the high amount of spruce, there was a trend that the larger parcels had a later timing of sanitary felling (1.8, SE = 1.04). In the area with the ice storm, there was no association between parcel area and timing where there was a low amount of spruce (1.13, SE = 1.38), while where there was a high amount of spruce, the larger parcels had an earlier timing of sanitary felling (–3.24, SE = 1.53).

For property size and the amount of sanitary felling, in the larger properties (–0.61, SE = 0.31) and areas with more sanitary felling (–0.92, SE = 0.31), the timing of the sanitary felling was earlier.

The Nagelkerke R^2 was low, at 0.08, and the RMSE was similar in the training set and the validation set (25 vs. 25.7, respectively). There was no spatial autocorrelation observed when using the spatial lag test (test value = 2.6807, p = 0.10). Including the spatial terms improved the model (AIC spatial lag model: 38819; AIC lm: 39066)

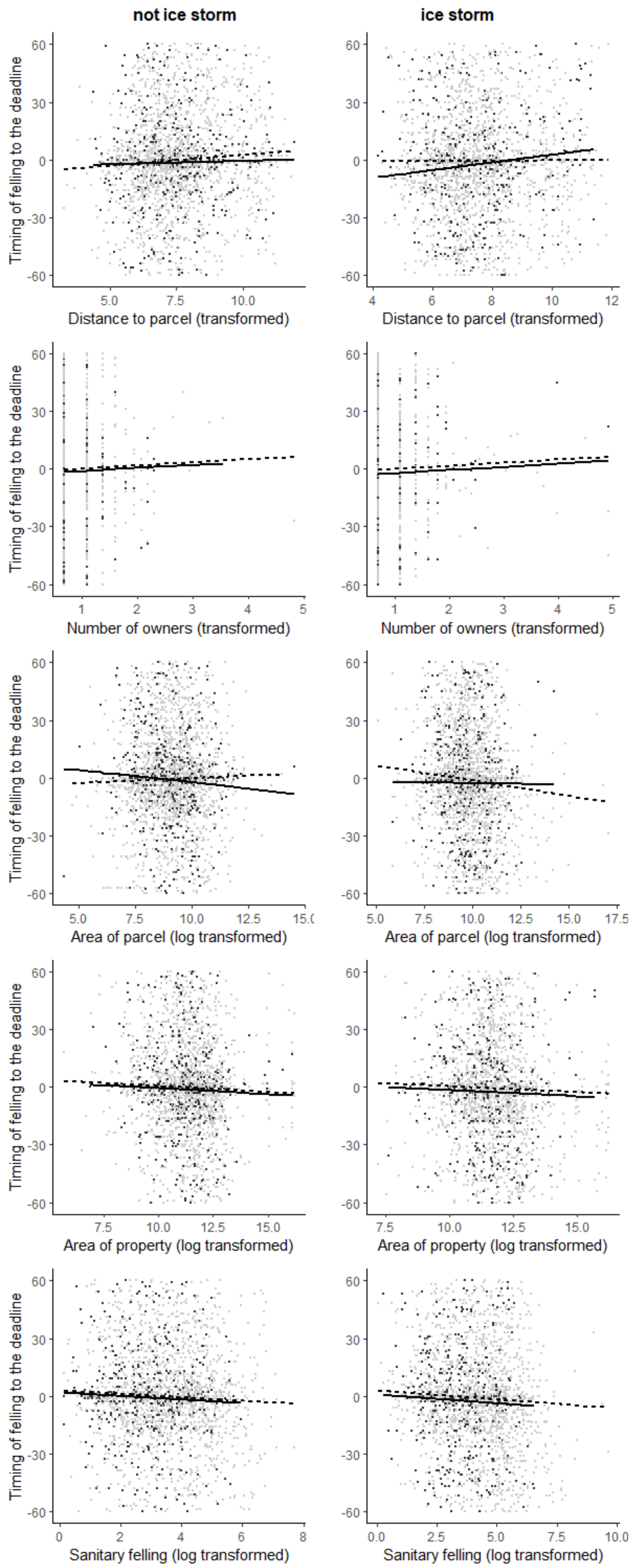

Figure 3. Associations of the different characteristics of the privately owned parcels with the presence of the ice storm and the amount of spruce with the timing of felling in the winter period. The grey dots and the black dashed line show a high amount of spruce, and the black solid line and black dots show a low amount of spruce.

4. Discussion

The results show that disturbance and the amount of spruce affect the influence of forest owner characteristics on bark beetle management. As hypothesized, the amount and timing of sanitary felling were positively associated with distance to the parcel, but not in summer, and in winter, there was a more complex association (Table 4). Moreover, this association was stronger in disturbed areas. Co-ownership positively affected the timing of sanitary felling, especially in disturbed areas but had no association with the amount of sanitary felling. Larger parcels were more affected by bark beetles, but the timing of cutting in the summer period was not later as hypothesized. The timing was more affected by the amount of spruce and the presence of the ice storm. Hypothesis 4 about the owners was correct with respect to the amount and timing of sanitary felling, as the amount increased, and the timing decreased with property size. The strength of this association was influenced by the degree of disturbance in the area. Hypothesis 5 was also correct with respect to the size of the settlement of the private owner and the timing of sanitary felling. For the amount of sanitary felling, there was no association with the size of the settlements. However, for the timing of sanitary felling in the winter, there was no association. The correlation between forest owner age and amount and timing of sanitary felling did not show any association and was therefore rejected. Gender did not seem to have an important influence on any of the assessed variables, and therefore, Hypothesis 7 was confirmed. Interestingly, the amount of sanitary felling was only positively correlated with timing in the summer but not in the winter.

In the analysis of the literature, little was found that directly relates the effect of private forest owner structure (age, gender, distance to the forest parcel or settlement in urban areas) on spruce bark beetle management. The hypothesis that older forest owners with more experience in forest management are more careful and notice an attack sooner and therefore cut earlier was rejected. The influence of the age of forest owners on forest management is not trivial in general. Researchers [53] analyzing family forest owner characteristics in the USA stated that it makes sense that forest use variables would be negatively associated with the age of forest owners. Several studies have reported that among socio-demographic variables, age has a negative effect on harvesting intensity [54–56], but some other studies have found a positive relationship between these two variables [57]. Research carried out among private forest owners in Slovenia showed that there was no statistical significance between the age of the owner and the intensity of forest management. Forest owners in all age groups managed their forests with similar intensity (20 m^3/ha over a period of five years) [58]. Previous studies have also indicated that younger owners are more likely to consider selling timber [59] and are more interested in business integration [60].

A study among private forest owners in southern Vermont and western Massachusetts, USA, confirmed that the duration of ownership and distance from the residence to the forest holding were significant in explaining the motivations of forest owners. Notably, owners living far away from their forest property were particularly disinterested in timber production [61]. Results from research among private forest owners in Slovenia are similar [62]. Forest owners whose forest property is less than 10 km from their residence were more active in forest management. Overall, 65% of the total amount of harvested wood reported by survey respondents was felled by owners whose forest properties were close to their residence. Moreover, Kumer and Štrumbelj [63] argued that the spatial patterns of owner residences and forest property influence management decisions. They found that engaged owners live closer to their land than detached owners. The influence of the large distance from the forest parcel to the forest owner residence was part of Hypothesis 1, which was confirmed for the amount and timing of sanitary felling in winter but rejected for the timing of summer sanitary felling.

Table 4. Confirmation (+), partial confirmation (+/–), or rejection (–) of the hypotheses on the influence of forest owner characteristics on bark beetle management according to the results.

	Hypotheses	Amount of Sanitary Felling	Timing of Summer Sanitary Felling	Timing of Winter Sanitary Felling
1.	A large distance between the forest parcel and the forest owner's residence is more likely to be expressed in less active forest management and consequently in later cutting and more outbreaks.	+	–	+/-
2.	Co-ownership of forest parcels can have a negative influence on forest management and therefore result in delays in the cutting of attacked trees.	–	+	+
3.	Large parcels have more spruce and therefore a higher potential of sanitary felling and later timing of cutting.	+	+/–	+/-
4.	Larger forest owners have more outbreaks but are more active in forest management, more experienced, better equipped for forest operations, and have better connections to forest contractors and therefore cut earlier.	+/–	+	+
5.	Forest owners living in urban areas are less active in forest management, resulting in more outbreaks and later cutting.	–	+	-
6.	Older forest owners with more experience in forest management are more careful and notice attacks sooner and therefore cut earlier.	–	–	-
7.	Gender of forest owners has no specific influence on forest management activities and therefore also on the timing of sanitary felling.	+	+	+

Distance to the parcel can also be linked to the type of settlement in which the forest owner resides (urban/rural), which was addressed in Hypothesis 5, although no correlation was found between them. Research carried out among private forest owners [64] confirmed that factors such as the importance of income from the forest and membership in a forest owners' association have a stronger impact on the choice of management strategy than factors related to the distance between the owner's residence and the forest property. Similar conclusions were also drawn by Nordlund and Westin [65], who reported that forest revenues are more important to resident owners than to non-resident owners, which might cause the latter to have more production-oriented forest values and economic management attitudes. This can also be linked to our Hypothesis 5 that forest owners living in urban areas are less active in forest management, and have therefore later cutting, although we did not find an influence on sanitary felling. Independent research carried out among private forest owners in Slovenia showed that there is no statistical significance between the type of settlement where the forest owners reside (urban/rural) and the intensity of forest management [51].

Private forest management is far from optimal, especially in Slovenia, which is the result of diverse ownership and property structure. This diversity is displayed in many owners (around 314,000) and co-owners (around 489,000), small forest property (on average <3 ha), and fragmentation (three plots on average) [66]. Research carried out by the Slovenian Forestry Institute among private forest owners in 2011 showed that large private forest owners (over 20 ha of forest property) represent a larger share of those owners who co-own forest property [62]. According to Poje et al. [67], harvesting intensity decreases with the number of owners and co-owners. The form of ownership also influences the willingness of forest owners to cooperate in managing their forests [68]. The study showed that the greatest interest in co-operation was on the part of respondents who are joint owners of forest property and share a common household with their co-owners. Furthermore, the greatest willingness to cooperate was expressed by the forest owner [68]. Hypothesis 2 is in line with these findings, and although we did not find that co-ownership of the forest parcels had a negative influence on sanitary felling, it caused delays in the cutting of attacked trees.

Hypothesis 3 can be explained simply by stand characteristics rather than forest owner characteristics. Larger parcels have more spruce and therefore have a higher chance of being attacked. The correlation between the size of the parcel and the timing of cutting is also positive in non-disturbed areas because of the larger amount of spruce, which delays the timing of the cutting. However, interestingly, this correlation was negative in areas with disturbance because the owners were urged to clean up the bark beetle attacked trees as soon as possible. However, more research is needed to better understand the interaction between sanitary felling due to bark beetles and parcel size under different disturbance regimes.

Our Hypothesis 4 that forest owners with larger properties have more outbreaks but are more active in forest management, have more experience, are better equipped for forest operation, and have better connections to forest contractors and therefore cut earlier was partly confirmed. In fact, property size is one of the most frequently used variables in timber harvesting studies, and the majority of studies have confirmed the positive effect of property size on harvesting interest and intensity [21,55,64,67], and on response time [69].

However, Bashir et al. [70] found that the forest size and timber harvest intensity are negatively correlated. In addition, forest size was inversely related to timber supply because of the higher productivity and larger growing stock recorded on smaller properties.

Several studies have confirmed that forest owners with larger forest properties are more open to business cooperation [60] and the affinity for subsidies [71]. Furthermore, research among Slovenian private forest owners who actively managed their forests in the last five years showed that larger forest owners are more active in harvesting, and a higher percentage of them hire professional forestry contractors in comparison to smaller forest owners [58].

The intensity of forest management is influenced by the size and fragmentation of the property [68]. Furthermore, the study emphasized that the owners of forest properties larger than 30 ha are the most interested in cooperating with other forest owners for efficient forest management. In addition, the results also showed that the owners of more fragmented forest properties cooperate more often and are also more willing to cooperate than owners of less fragmented forest properties. The size of the forest property also affects the intensity of forest management in terms of accessibility of the forest area to forest operations [67]. Extraction distance was found to negatively influence harvesting intensity.

According to the data analyzed in this study, we confirmed that the gender of forest owners has no specific influence on forest management activities and therefore also on the timing of sanitary felling. Due to changes in inheritance practices and other societal changes, female forest ownership has increased across Europe and is currently estimated to be about 30% on average of all small-scale forest property holders [14]. A study among private forest owners in Sweden showed that female forest owners have a stronger attitude toward ecological and recreational forest values and the environmental aspects of forest management. Nevertheless, there were no significant gender differences in forest values and forest management attitudes [65]. A recent study on gender differences in private forest risk management among forest owners in Sweden confirmed a slightly lower level of forest risk management among female owners in proactively combating damage caused by climate change and animal browsing when compared to their male counterparts [72]. Another study in Sweden found that the differences in final felling and silvicultural activities between male and female forest owners were not apparent. However, the differences regarding production values and ecological values, and to some extent cultural values, were significant [73]. A study in Finland observed that female owners harvested 30% less timber than male owners [74]. Similar trends were confirmed by research carried out among private forest owners in Slovenia [58], with low statistical significance between gender and forest management intensity.

Interestingly, the models explained only a relatively small part of the variability, especially for the timing of sanitary felling. This can be explained by the fact that ecological and sociological data were not included. First, bark beetles are affected by many ecological factors, such as temperature, slope, the position of the tree, and other natural disturbances [26,75]. These factors have a large influence on the outbreak dynamics of bark beetles; however, they were not the focus of this study. We show that a large part of the variability was explained by forest owners, especially with respect to the amount of sanitary felling. It would be relevant for models focusing on outbreak distribution or forecasting to include also forest owner-related factors because this could increase their performance. Another reason could be missing sociological data. Other aspects of sociological data, such as level of education, information, knowledge, and acceptance of bark beetle management, dependence on forestry income, integration of owners into associations, personal attitude toward forests and forest management, and forest openness because of the forest road network, could explain the timing of sanitary felling [21,76]. However, in this study, the only available data were those that were described in the Methods Section. Further study on forest owners should show how other social aspects affect the timing of sanitary felling. The third reason for the low explained variability could be that in the period of the study (2014–2018), there was an overload of wood on the national wood market because of the ice storm and several windthrows [77]. The increased pressure to remove trees damaged by the ice storm and windthrows, together with the unavailability of contractors for forestry services and saturation of the market, could have delayed the timing of the sanitary felling of bark beetle-infested trees [69]. Further studies should investigate to what extent the availability of wood due to other natural disturbances could have affected the timing of sanitary felling of bark beetles-infested trees.

Implications for Bark Beetle Management

Forest owner characteristics were strongly associated with the amount of sanitary felling due to bark beetles and revealed how forest owners can be involved in the management of bark beetle outbreaks. We highlight here groups that are especially vulnerable when large bark beetle outbreaks occur. Forest owners who have large stands and properties, more co-owners, live further away from their property, and live in cities have a higher chance of experiencing large outbreaks. This is especially true in areas with a larger amount of spruce or affected by natural disturbances. Interestingly, the timing of cutting is only delayed when there are more co-owners, larger parcels, and owners who live closer to their property and in larger settlements. Policymakers and national forest services should take these risk groups into account, and we strongly advise policymakers and forest services to constructively assist these groups in dealing with bark beetle outbreaks. There are many possible solutions that can help forest owners to salvage their forests damaged in large-scale outbreaks. It is known that incentives and the provision of equipment help forest owners to react more quickly to bark beetle outbreaks [21,67,78,79]. It is important to know that the timing of felling in the winter is relatively less important, and when help is needed, the main focus should be in the vegetation period when bark beetles are more active [24].

It has been shown that short-term activities such as sanitary felling at low to medium intensities will only dampen the effect of outbreaks rather than avoid them altogether, except in the case of the early and concentrated removal of damaged or weakened trees, when the impact of bark beetles can be substantially reduced [76]. Therefore, a long-term forest management plan should be developed in which forest owners are also included. In Slovenia and most other Central European countries, non-industrial forest owners predominate. These owners have traditionally focused on forest management, which avoids clear-cutting and promotes uneven-aged mixed forests. Research shows that there is generally less sanitary logging [80] associated with this type of forestry and that such stands recover faster following natural disturbances [81–83]. However, the management method alone is not sufficient without active intervention in the development of the forest. In the past, the forest often served as an investment or reserve for emergencies, especially among older owners who are less willing to carry out felling [67]. Due to climate change, regular management is becoming increasingly important for bark beetle management [12], and hence it would make sense to promote it through a mix of forest policy measures.

In conclusion, forest owner activities and characteristics are important for bark beetle management, in addition to the already known environmental factors [24,75]. In the coming decades, forests will be increasingly threatened by climate change and catastrophic events, which will consequently facilitate bark beetle outbreaks [4,8,25]. To date, the main focus has been on short-term actions dealing with the biology and ecology of species. Raising awareness among forest owners and forest services and other bark beetle management-related institutions about forest owner vulnerabilities, especially those at greater risk, would increase the potential to detect possible outbreaks early enough to mitigate them. It is therefore of utmost importance that further bark beetle management measures are tested among private forest owners in order to decrease the effect of bark beetle outbreaks in a fast-changing world.

Author Contributions: Conceptualization, M.d.G., N.O. and R.P.; formal analysis, M.d.G.; data curation, N.O., R.P., and K.K.; writing—original draft preparation, M.d.G., J.D., K.K., N.K., R.P., Š.Š., D.S., and N.O.; writing—review and editing, M.d.G., J.D., K.K., N.K., R.P., Š.Š., D.S., and N.O. All authors have read and agreed to the published version of the manuscript.

Funding: The study was possible with help of the Public Forest Service of the Ministry of Agriculture, Forestry, and Food and the research core group "Forest biology, ecology, and technology" (P4-0107) financed by the Slovenian Research Agency.

Acknowledgments: We would like to thank the foresters from the Slovenia Forest Service who go into the field every day and keep the forest and bark beetle databases up to date.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Nagel, T.A.; Mikac, S.; Dolinar, M.; Klopcic, M.; Keren, S.; Svoboda, M.; Diaci, J.; Boncina, A.; Paulic, V. The natural disturbance regime in forests of the Dinaric Mountains: A synthesis of evidence. *For. Ecol. Manag.* **2017**, *388*, 29–42, doi:10.1016/j.foreco.2016.07.047.
2. Seidl, R.; Schelhaas, M.-J.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806–810, doi:10.1038/nclimate2318.
3. Lorenzo, M.; Ayres, M.; Battisti, A.; Faccoli, M. Climate Affects Severity and Altitudinal Distribu-tion of Outbreaks in an Eruptive Bark Beetle. *Clim. Chang.* **2012**, *155*, 327–341.
4. de Groot, M.; Ogris, N.; Kobler, A. The Effects of a Large-Scale Ice Storm Event on the Drivers of Bark Beetle Outbreaks and Associated Management Practices. *For. Ecol. Manag.* **2018**, *408*, 195–201.
5. Lorenzo, M.; Økland, B.; Jönsson, A.M.; Bentz, B.; Carroll, A.; Forster, B.; Grégoire, J.; Hurling, R.; Nageleisen, L.M.; Netherer, S.; Ravn, H.P.; Weed, A.; et al. Climate Drivers of Bark Beetle Outbreak Dynamics in Norway Spruce Forests. *Ecography* **2017**, *40*, 1426–1435.
6. Potter, C.; Urquhart, J. Tree disease and pest epidemics in the Anthropocene: A review of the drivers, impacts and policy responses in the UK. *For. Policy Econ.* **2017**, *79*, 61–68, doi:10.1016/j.forpol.2016.06.024.

7. Haavik, L.J.; Billings, S.A.; Guldin, J.M.; Stephen, F.M. Emergent insects, pathogens and drought shape changing patterns in oak decline in North America and Europe. *For. Ecol. Manag.* **2015**, *354*, 190–205, doi:10.1016/j.foreco.2015.06.019.
8. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, M.P.J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402, doi:10.1038/nclimate3303.
9. Raffa, K.F.; Aukema, B.H.; Bentz, B.J.; Carroll, A.L.; Hicke, J.A.; Turner, M.G.; Romme, W.H. Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *Bioscience* **2008**, *58*, 501–517, doi:10.1641/b580607.
10. Jactel, H.; Brockerhoff, E.G. Tree diversity reduces herbivory by forest insects. *Ecol. Lett.* **2007**, *10*, 835–848, doi:10.1111/j.1461-0248.2007.01073.x.
11. Faccoli, M.; Bernardinelli, I. Composition and Elevation of Spruce Forests Affect Susceptibility to Bark Beetle Attacks: Implications for Forest Management. *Forests* **2014**, *5*, 88–102, doi:10.3390/f5010088.
12. de Groot, M.; Diaci, J.; Nikica Ogris, N. Forest Management History Is an Important Factor in Bark Beetle Outbreaks: Lessons for the Future. *For. Ecol. Manag.* **2019**, *433*, 467–474.
13. Pamela, P.; Schuck, A.; Verkerk, P.J.; Lasserre, B.; Marchetti, M.; Green, T. *Mapping the Distribution of Forest Ownership in Europe*; EFI Technical Report; European Forest Institute: 2013; Volume 91.
14. Weiss, G.A.; Lawrence, G.; Lidestav, D.; Feliciano, T.; Hujala, Z.; Sarvašová, Z.; Dobšinská, Z.; Živojinović, I. Research trends: Forest ownership in multiple perspectives. *For. Policy Econ.* **2019**, *99*, 1–8.
15. Matilainen, A.; Koch, M.; Zivojinovic, I.; Lähdesmäki, M.; Lidestav, G.; Karppinen, H.; Didolot, F.; Jarsky, V.; Põllumäe, P.; Colson, V.; et al. Perceptions of ownership among new forest owners—A qualitative study in European context. *For. Policy Econ.* **2019**, *99*, 43–51, doi:10.1016/j.forpol.2018.06.002.
16. Živojinović, I.G.; Weiss, G.; Lidestav, D.; Feliciano, T.; Hujala, Z.; Dobšinská, A.; Lawrence, E.; Nybakk, S.Q.; Schraml, U. Forest Land Ownership Change in Europe. In *COST Action FP1201 FACESMAP Country Reports*, *Joint Volume, EFICEEC-EFISEE Research Report*; University of Natural Resources and Life Sciences, Vienna (BOKU): Vienna, Austria, 2015; Volume 693.
17. Ficko, A.; Lidestav, G.; Ní Dhubháin, Á.; Karppinen, H.; Zivojinovic, I.; Westin, K. European Private Forest Owner Ty-pologies: A Review of Methods and Use. *For. Policy Econ.* **2019**, *99*, 21–31.
18. Bouriaud, L.; Nichiforel, L.; Weiss, G.; Bajraktari, A.; Curovic, M.; Dobsinska, Z.; Glavonjic, P.; Jarský, V.; Sarvasova, Z.; Teder, M.; et al. Governance of private forests in Eastern and Central Europe: An analysis of forest harvesting and manage-ment rights. *Ann. For. Res.* **2013**, *56*, 199–215.
19. Ni Dhubháin, Á.; Cobanova, R.; Karppinen, H.; Mizaraite, D.; Ritter, E.; Slee, B.; Wall, S. The Val-ues and Objectives of Private Forest Owners and Their Influence on Forestry Behaviour: The Implications for Entrepreneur-ship. *Small-Scale For.* **2007**, *6*, 347–357.
20. Ott, E.; Frehner, M.; Frey, H.-U.; Lüscher, P. *Gebirgsnadelwälder: Praxisorientierter Leitfaden Für Eine Standortgerechte Waldbehandlung;* Verlag Paul Haupt: Wien, Austria, 1997.
21. Molnar, J.J.; Schelhas, J.; Carrie, H. Nonindustrial Private Forest Landowners and the Southern Pine Beetle: Factors Affecting Monitoring, Preventing, and Controlling Infestations. *South. J. Appl. For.* **2007**, *31*, 93–98, doi:10.1093/sjaf/31.2.93.
22. She, J.; Chung, W.; Han, H. Economic and Environmental Optimization of the Forest Supply Chain for Timber and Bio-energy Production from Beetle-Killed Forests in Northern Colorado *Forests* **2019**, *10*, 689.
23. Malovrh, Š.P.; Nonić, D.; Glavonjić, P.; Nedeljković, J.; Avdibegović, M.; Krč, J. Private Forest Owner Typologies in Slo-venia and Serbia: Targeting Private Forest Owner Groups for Policy Implementation. *Small-Scale For.* **2015**, *14*, 423–440.
24. Wermelinger, B. Ecology and management of the spruce bark beetle Ips typographus—a review of recent research. *For. Ecol. Manag.* **2004**, *202*, 67–82, doi:10.1016/j.foreco.2004.07.018.
25. Pavel, M.; Jakuš, R.; Pennerstorfer, J.; Potterf, M.; Jaroslav, S.; Ferenčík, J.; Slivinský, J.; Bičárová, S.; Bilcik, D.; Blazenec, M.; et al. *Storms, Temperature Maxima and the Eurasian Spruce Bark Bee-Tle Ips Typographus—An Infernal Trio in Norway Spruce Forests of the Central European High Tatra Mountains*; Agricultural and Forest meteorology. 2017; Volume 242.
26. de Groot, M.; Ogris, N. Short-Term Forecasting of Bark Beetle Outbreaks on Two Economically Important Co-nifer Tree Species. *For. Ecol. Manag.* **2019**, *450*, 117495.
27. Netherer, S.; Panassiti, B.; Pennerstorfer, J.; Matthews, B. Acute Drought Is an Important Driver of Bark Beetle Infestation in Austrian Norway Spruce Stands. *Front. For. Glob. Chang.* **2019**, *2*, doi:10.3389/ffgc.2019.00039.
28. Hervé, J.; Koricheva, J.; Castagneyrol, B. Responses of Forest Insect Pests to Climate Change: Not So Sim-ple. *Curr. Opin. Insect Sci.* **2019**, *35*, 103–108.
29. Oliver, J.; Lischke, H.; Wermelinger, B. Climate Change Alters Elevational Phenology Patterns of the Euro-pean Spruce Bark Beetle (Ips Typographus). *Glob. Chang. Biol.* **2019**, *25*, 4048–4063.

30. Tom, L.; Gričar, J.; Gagen, M.; Jalkanen, R.; Loader, N.; McCarroll, D.; Oven, P.; Robertson, I. The Climate Sensitivity of Norway Spruce [Picea Abies (L.) Karst.] in the Southeastern European Alps. *Trees* **2009**, *23*, 169–180.
31. Nealis, V. A risk analysis framework for forest pest management. *For. Chron.* **2015**, *91*, 32–39, doi:10.5558/tfc2015-008.
32. Mlinšek, D. Clear-Cutting to a Close-to-Nature Silvicultural System. *Iufro News* **1996**, *25*, 6–8.
33. Thomas, A.N.; Firm, D.; Pisek, R.; Mihelic, T.; Hladnik, D.; de Groot, M.; Rozenbergar, D. Evaluating the Influence of Integrative Forest Management on Old-Growth Habitat Structures in a Temperate Forest Re-gion. *Biol. Conserv.* **2017**, *216*, 101–107.
34. ZGS. *State of Forests in Slovenia*; Slovenia Forest Service: Ljubljana, Slovenia, 2019.
35. Zupančič, M.; Marinček, L.; Seliškar, A.; Puncer, I. Considerations on the Phytogeographic Division of Slovenia. *Bioge-Ographia* **1987**, *13*, 89–98.
36. Bončina, A.; Klopčič, M.; Simončič, T.; Dakskobler, I.; Ficko, A.; Rozman, A. A General Framework to Describe the Altera-tion of Natural Tree Species Composition as an Indicator of Forest Naturalness. *Ecol. Indic.* **2017**, *77*, 194–204.
37. ZGS. *Timber 2014–2018, Database About Felling in the Slovenia*; Slovenia Forest Service: Ljubljana, Slovenia, 2019.
38. GURS. *Cadastral Register, Spatial Database*; Surveying and Mapping Authority of the Republic of Slovenia: Ljubljana, Slovenia, 2016.
39. ZGS. *Forest Stand. Map in Slovenia, Spatial Database*; Slovenia Forest Service: Ljubljana, Slovenia, 2017.
40. GURS. *Register of Spatial Units, Settlements, Post Districts, Streets, House Numbers*; Surveying and Mapping Authority of the Republic of Slovenia: Ljubljana, Slovenia, 2019.
41. Zuur, A.F.; Ieno, E.N.; Elphick, C.S. A protocol for data exploration to avoid common statistical problems: Data exploration. *Methods Ecol. Evol.* **2010**, *1*, 3–14, doi:10.1111/j.2041-210x.2009.00001.x.
42. Anselin, L. *Spatial Econometrics: Methods and Models*; Kluwer Academic Publishers: Boston, MA, USA, 1988.
43. Dray, S.; Legendre P.; Peres-Neto. P. R. Spatial Modeling: A Comprehensive Framework for Principle Coordinate Analysis of Neighbor Matrices (PCNM). Ecol. Model. 2006,196: 483–93.
44. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2017.
45. Hamner, B.; Frasco, M. Metrics: Evaluation Metrics for Machine Learning. R package version 0.1.4., 2018, https://CRAN.R-project.org/package=Metrics
46. Hadley, W. *Ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2016.
47. Kassambara, A. Ggpubr: 'Ggplot2' Based Publication Ready Plots. R package version 0.3.0., 2020, https://CRAN.R-project.org/package=ggpubr
48. Bivand, R.; Piras, G. Comparing Implementations of Estimation Methods for Spatial Econometrics. *J. Stat. Softw.* **2015**, *63*, doi:10.18637/jss.v063.i18.
49. Bivand, R.S.; Hauke, J.; Kossowski, T. Computing the Jacobian in Gaussian Spatial Autoregressive Models: An Illus-trated Comparison of Available Methods. *Geogr. Anal.* **2013**, *45*, 150–179.
50. Zhang, Y. Likelihood-based and Bayesian methods for Tweedie compound Poisson linear mixed models. *Stat. Comput.* **2012**, *23*, 743–757, doi:10.1007/s11222-012-9343-7.
51. Dray, S.; Bauman, S.; Blanchet, G.; Borcard, D.; Clappe, S.; Guenard, G.; Jombart, T.; Larocque, G.; Legendre, P.; Madi, N.; Wagner, J.H. Adespatial: Multivariate Multiscale Spatial Analysis Version R package version 0.1-1. https://CRAN.R-project.org/package=adespatial
52. Lesage, J.P.; Fischer, M.M. Spatial Growth Regressions: Model Specification, Estimation and Interpretation. *Spat. Eco-Nomic Anal.* **2008**, *3*, 275–304.
53. Butler, S.; Butler, B.J.; Markowski-Lindsay, M. Family Forest Owner Characteristics Shaped by Life Cycle, Cohort, and Period Effects. *Small-Scale For.* **2016**, *16*, 1–18, doi:10.1007/s11842-016-9333-2.
54. Karppinen, H. New forest owners and owners-to-be: Apples and oranges? *Small-Scale For.* **2011**, *11*, 15–26, doi:10.1007/s11842-011-9165-z.
55. Beach, R.; Pattanayak, S.K.; Yang, J.-C.; Murray, B.C.; Abt, R.C. Econometric studies of non-industrial private forest management: A review and synthesis. *For. Policy Econ.* **2005**, *7*, 261–281, doi:10.1016/s1389-9341(03)00065-0.
56. Størdal, S.; Lien, G.; Baardsen, S. Analyzing determinants of forest owners' decision-making using a sample selection framework. *J. For. Econ.* **2008**, *14*, 159–176, doi:10.1016/j.jfe.2007.07.001.
57. Jianbang, G.; Kebede, E. Multivariate Probit Modeling of Decisions on Timber Harvesting and Request for Assistance by African-American Forestland Owners. *South. J. Appl. For.* **2005**, *29*, 135–142.
58. Ščap, Š.; Stare, D.; Krajnc, N. *Poročilo O Stanju Na Področju Izvajanja Poseka in Spravila V Zasebnih Gozdovih*; 2020. Slovenian Forestry Institute, Ljubljana
59. Ma, Z.; Kittredge, D.B. How Family Forest Owners Consider Timber Harvesting, Land Sale, and Conservation Easement Decisions: Insights from Massachusetts, USA. *Int. J. For. Res.* **2011**, *2011*, 1–13, doi:10.1155/2011/290353.

60. Malovrh, Š.P.; Laktić, T. Forest Owners' Business Integration as in the Case of Pohorje-Kozjak Forest Owners Society. *Acta Silvae Et Ligni* **2017**, *113*, doi:10.20315/ASetL.113.1.
61. Rickenbach, M.; Kittredge, D.B. Time and Distance: Comparing Motivations among Forest Landowners in New Eng-land, USA. *Small-Scale For.* **2009**, *8*, 95–108.
62. Medved, M.; Robek, R. *Projekt Nove Poti Za Razvoj Trajnostnega Pridobivanja in Rabe Lesa V Sloveniji: Ciljni Ra-Ziskovalni Program*; *Slovenia Forestry Institute*, Ljubljana, Slovenia, 2011.
63. Kumer, P.; Štrumbelj, E. Clustering-Based Typology and Analysis of Private Small.Scale Forest Owners in Slovenia. *For. Policy Econ.* **2017**, *80*, 116–124.
64. Eggers, J.; Lämås, T.; Lind, T.; Öhman, K. Factors Influencing the Choice of Management Strategy among Small-Scale Private Forest Owners in Sweden. *Forests* **2014**, *5*, 1695–1716.
65. Nordlund, A.M.; Westin, K. Forest Values and Forest Management Attitudes among Private Forest Owners in Sweden. *Forests* **2010**, *2*, 30–50, doi:10.3390/f2010030.
66. Medved, M.; Matijasic, D.; Pisek, R. Private Property Conditions of Slovenian Forests:Preliminary Results from 2010. In Proceedings of the Paper Presented at the IUFRO Conference Proceedings Small-Scale Forestry in a Changing World: Opportunities and Challenges and the Role of Extension and Technology Transfer, Ljubljana, Slovenia, 6–10 June 2010.
67. Poje, A.; Malovrh, Š.P.; Krč, J. Factors Affecting Harvesting Intensity in Small-Scale Private Forests in Slovenia. *Small-Scale For.* **2016**, *15*, 73–91, doi:10.1007/s11842-015-9309-7.
68. Pezdevšek Malovrh, Š.; Stirn, L.Z.; Krč, J. Influence of Ownership and Property Structure on Willingness of Private Forest Owners to Cooperate. *Sumar. List* **2010**, *134*, 3–4.
69. Kolšek, M. Pričakovani Vplivi Podnebnih Sprememb Na Sečnjo V Gozdu V Sloveniji. In Proceedings of the Paper presented at the Posvet Iz-Koriščanje Gozdnih Proizvodov V Slovenskem Gospodarstvu, Ljubljana, Slovenia, 16 November 2011.
70. Bashir, A.; Sjølie, H.K.; Solberg, B. Determinants of Nonindustrial Private Forest Owners' Willingness to Harvest Timber in Norway. *Forests* **2020**, *11*, 60.
71. Quiroga, S.; Suarez, C.; Ficko, A.; Feliciano, D.; Bouriaud, L.; Brahic, E.; Deuffic, P.; Dobsinska, Z.; Jarsky, V.; Lawrence, A.; et al. What influences European private forest owners' affinity for subsidies? *For. Policy Econ.* **2019**, *99*, 136–144, doi:10.1016/j.forpol.2018.08.008.
72. Eriksson, L. Explaining gender differences in private forest risk management. *Scand. J. For. Res.* **2018**, *33*, 716–723, doi:10.1080/02827581.2018.1453944.
73. Umaerus, P.; Nordin, M.H.; Lidestav, G. Do female forest owners think and act "greener"? *For. Policy Eco-Nomics* **2019**, *99*, 52–58.
74. Kuuluvainen, J.; Karppinen, H.; Hänninen, H.; Uusivuori, J. Effects of gender and length of land tenure on timber supply in Finland. *J. For. Econ.* **2014**, *20*, 363–379, doi:10.1016/j.jfe.2014.10.002.
75. Pasztor, F.; Matulla, C.; Rammer, W.; Lexer, M.J. Drivers of the bark beetle disturbance regime in Alpine forests in Austria. *For. Ecol. Manag.* **2014**, *318*, 349–358, doi:10.1016/j.foreco.2014.01.044.
76. Dobor, L.; Hlásny, T.; Rammer, W.; Zimová, S.; Barka, I.; Seidl, R. Spatial Configuration Matters When Removing Wind-felled Trees to Manage Bark Beetle Disturbances in Central European Forest Landscapes. *J. Environ. Manag. Ment* **2020**, *254*, 109792.
77. Mori, J.; Poljanec, A. Trenutne Aktivnosti in Izzivi Pri Preprečevanju Škod V Gozdovih Zaradi Ekstremnih Vremen-skih Pojavov. In *Gozd in Les Kot Priložnost Za Regionalni Razvoj*; Bončina, A., Oven, P., Eds.; Bio-Tehniška Fakulteta: Ljubljana, Slovenia, 2019; pp. 99–112.
78. Unay-Gailhard, I.; Štefan, B. Public support effect on natural disaster management: A case study of ice storms in forests in Slovenia. *Land Use Policy* **2020**, *95*, 103811, doi:10.1016/j.landusepol.2019.01.014.
79. Ales, K.; Avsenek, A.; Matjašič, M. A Word on the Workshop "Bark Beetle Problematics—The Search of Operative Solutions". *Gozdarski Vestn.* **2019**, *77*, 7–8.
80. Lenk, E.; Kenk, G. Sortenproduktion Und Risiken Schwarzwälder Plenterwälder. *Allg. Forstztg/Der Wald* **2007**, *62*, 136–139.
81. Schütz, J.-P.; Götz, M.; Schmid, W.; Mandallaz, D. Vulnerability of spruce (Picea abies) and beech (Fagus sylvatica) forest stands to storms and consequences for silviculture. *Eur. J. For. Res.* **2006**, *125*, 291–302, doi:10.1007/s10342-006-0111-0.
82. Schmid-Haas, P.; Bachofen, H. Die Sturmgefährdung von Einzelbäumen Und Beständen. *Schweiz. Z. Für Stwesen* **1991**, *142*, 477–504.
83. Diaci, J.; Roženbergar, D.; Fidej, G.; Nagel, T.A. Challenges for Uneven-Aged Silviculture in Restoration of Post-Disturbance Forests in Central Europe: A Synthesis. *Forests* **2017**, *8*, 378, doi:10.3390/f8100378.