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Characteristics of Forest Windthrow Produced in Eastern Carpathians in February 2020

Mihai Ciocirlan [1,2] and Vasile Răzvan Câmpu [1,*]

[1] Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Braşov, 500123 Braşov, Romania; mihai.ciocirlan@unitbv.ro
[2] Comandău Forest District, Covasna County Forest Administration, 525100 Sfântu Gheorghe, Romania
* Correspondence: vasile.campu@unitbv.ro; Tel.: +40-729-123-450

Abstract: Windthrow is a phenomenon that causes major changes to tree stand evolution by blowing down or breaking either isolated trees or entire tree stands, with a strong ecological, social and economic impact. Both scattered and large-scale windthrow occurred in spruce (*Picea abies* (L.) Karst.) tree stands of Romania. They affected surfaces of various dimensions from harvestable forests. Such a phenomenon took place in the Curvature Carpathians in February 2020. Large-scale windthrow occurred in this area in 1995 as well, in the upper watershed of Bâsca river. Using the climate data from February 2020, this paper aims to identify the manner in which factors such as climate and site conditions together with tree stand characteristic and the anthropogenic factor impacted and influenced the occurrence of windthrow. The results showed that the intensity of this phenomenon had maximum effects when the wind coming from north/northeast reached the maximum speed of 32 m·s^{-1}. Pure spruce tree stands situated on slopes with an inclination between 16 and 30° were mainly affected. Their position was counter to the wind direction, at an altitude between 1300 and 1500 m, on cambisols and spodosols. The analysis and statistical interpretation of data in the case of scattered and large-scale windthrow from the two management units showed that the same factors studied influence the variation of windthrow intensity in a different manner, or sometimes they do not influence it at all or they can only account for a small part of this variation.

Keywords: windthrow; wind snap; snow break; storm damage; spruce; Carpathian Mountains; forest ecosystem

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1. Introduction

Considering the ecological, economic and social role of forest in today's world, where the population has exceeded 8 billion inhabitants, forest management can only be sustainable via maintenance of a balance between the environment, the society and the economy. The production and protection functions of tree stands are processes that can be stimulated and guided by management practices in order for the structure of tree stands to meet ecological, economic and social needs. It is well known that these processes can sometimes be disrupted by natural and anthropogenic factors that can damage or destroy either the entire tree stand or only a number of trees from it. Knowledge of these factors and their effects, and especially of the measures that can be taken in order to prevent or minimise these effects, is becoming increasingly important nowadays [1]. One of the most important phenomena causing changes in the dynamics of tree stands is mechanical damage by windthrow, wind snap and snow break. All of these have significant implications from ecological, sociological and economic points of view [2,3]. Also, windthrow has an important impact on carbon stock by diminishing the carbon stocking capacity at tree level and by increasing carbon losses at soil level [4,5]. It is of the utmost importance to understand both the way in which these phenomena take place and their effects in order to take the correct measures for preventing them at the level of tree stands. At the same time, when harvesting timber from windthrow, working conditions are extremely difficult, and injury risks for the workers are very high [6,7].

In the last decades, Europe has been hit by a series of big storms that caused large-scale damage to forests. It is estimated that Europe registers, on average, two such storms annually [8]. The number may increase greatly given the estimated climate change [9]. Although it is widely accepted that the frequency and intensity of storms will increase in Central and Eastern Europe, the same thing might not be true of Eastern Europe. A recent study has shown that, in the case of Eastern Europe, this is debatable, with certain articles supporting the idea that the intensity and frequency of storms will increase and others stating that these will decrease [10]. Even a relatively small increase in wind speed brought by climate change could lead to an increased frequency and intensity of wind snap [11]. Wind snap and attacks by insects that find favourable life conditions in windthrow areas are the main factors that cause damage to forests [5].

Most frequently, windthrow in Europe takes place in autumn or winter and is associated with areas where atmospheric pressure is low [12]. In 1999, countries like France, Germany and Switzerland were affected by cyclone Lothar that caused windthrow of about 165 million m^3 of wood [13]. In the southwest of Germany, windthrow produced by cyclone Lothar amounted to a volume of more than 30 million m^3. To this, an additional volume of more than 7 million m^3 was lost in the following years as a result of insect attacks [14]. Significant damage to forests by windthrow was reported in 2005 as well, when cyclone Gudrun hit Sweden and caused a damage of 75 million m^3 [13]. In 2007, a volume of 49 million m^3 of wood was affected by cyclone Kyrill in Germany and the Czech Republic. Further on, in 2009 and 2019, France and Spain lost 45 million m^3 of wood as a result of cyclones Klaus and Xynthia. In 2018, in the northeast of Italy, 8.5 million m^3 of wood was affected by storm Vaia [15].

Although windthrow can take place in most types of forests, it is widely acknowledged that Norway spruce (*Picea abies* (L.) Karst.) is one of the most vulnerable species compared to other conifers or broadleaf species [16–19].

In Romania, the oldest windthrow recorded in the literature in the field happened in 1828 in the forests of Sinaia and in 1843 in the forests of Bucovina [20]. More similar events were recorded in the following years of 1947–1948, 1964, 1969, 1975, 1982, 1995, 2002, 2009 [20–22]. Statistically speaking, almost 28% of Romanian forests are prone to windthrow and wind snap [23].

In 2020, in Romania, large areas of forests, both public and private property administered by the National Forest Administration—Romsilva—were affected by windthrow, wind snap and snow break [24]. A total surface of approximately 144,000 hectares was affected—16,000 hectares of large-scale windthrow and a volume of approximately 2.7 million m^3 covering 16 counties. The most affected counties from the point of wood volume were Mureș (23%), Argeș (18%), Prahova (14%), Harghita (11%), Suceava (8%), Covasna (6%) and Bacău (5%). In the other counties, the wood volume affected represents approximately 15% of the total volume. The surface affected is not correlated with the volume affected. Thus, the largest areas affected were in Suceava (32%), Mureș (14%), Prahova (9%), Harghita and Bacău (8%), Maramureș (6%) and Argeș (5%). In the rest of the counties, the surface affected represented less than 5%. In Covasna County, where this research study was carried out, the total area affected amounted to approximately 5860.41 hectares out of which 172.55 hectares were affected by large-scale windthrow. The volume affected was 160,810 m^3 [24].

Generally speaking, windthrow is determined by natural and anthropogenic causes, the natural ones being produced by dynamic factors such as air circulation as well as static factors at the level of the active surface (relief, forests and soil). The factors influencing the probability of storm damage in forests may be divided into four groups: meteorological conditions, site conditions, topographic conditions, tree and stand characteristics [25]. Anthropogenic causes include ecosystem artificialisation, pollution and greenhouse effect [26].

The artificialisation of forest ecosystems has taken place by replacing natural tree stands with artificial spruce tree stands ever since the 19th century in Central and Western Europe and starting with the 20th century in Romania. For economic reasons, monocultures followed by clear felling on large surfaces have led to a diminished natural resistance of forest ecosystems and, unavoidably, to the degradation of spruce tree stands [26]. Air pollution, especially by greenhouse gases, leads to the greenhouse effect and thus climate change [27], including the frequency and intensity of storms [28]. Thus, the increase in damage caused by windthrow and wind snap is due to the interaction between climate change and management strategies. These can lead to an increased vulnerability of trees and tree stands [29].

The aim of this paper is to find out the way in which climate conditions, site conditions, tree stand characteristics and anthropogenic factors acted and favoured the occurrence of windthrow in tree stands from the upper watershed of Bâsca river administered by the Forest District of Comandău by indicating the surfaces and volume of wood affected. The paper sets out to provide objective information regarding windthrow and its effect on spruce tree stands from Eastern Carpathians—a region with very few international publications regarding this aspect.

2. Materials and Methods

This research was conducted in areas affected by windthrow and wind snap in February 2020, in the Curvature Carpathians at the contact zone between Brețcului Mountains, Vrancei Mountains and Buzăului Mountains in the upper third of the watershed formed by rivers Bâsca Mare and Bâsca Mică. The area studied is located in the southwestern part of Covasna County and the northern part of Buzău County. The areas studied are part of the forests administered by the Forest District of Comandău, a part of Covasna County Forest Administration. They are all part of the National Forest Administration—Romsilva, and encompass Management Units Dealul Negru and Bâsca Mare (Figure 1).

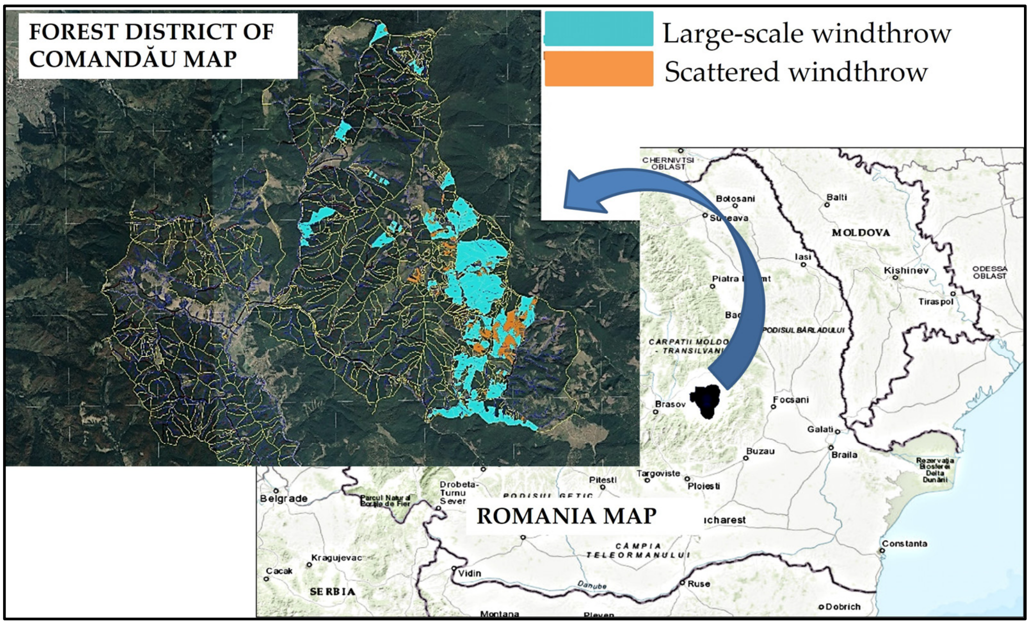


Figure 1. Research Venue—Forest District of Comandău.

Because windthrow also took place in the past in the studied area, the Forest District of Comandău that administers the forests in this area owns an archive where events like this are recorded together with the circumstances under which they occurred, as well as the surfaces and volume of wood affected. Therefore, this research involved the study of this archive.

Windthrow produced in the Forest District of Comandău was studied before the phenomenon analysed in this paper, especially after the large-scale windthrow produced on the 5th and 6th of November, 1995 and the endemic windthrow from 2000 to 2009 [26,30–35]. In November 1995, the area administered by Covasna County Forest Administration was affected by windthrow on an plot of 23,293 hectares and a volume of 2.649 million m^3 was damaged [36]. In the Forest District of Comandău, an area of approximately 9000 hectares was affected, resulting in a volume loss of 1.100 million m^3. Referring to the same period of time, in [34], it is stated that the total surface affected in the Covasna County Forest Administration was of 33,225.5 hectares, resulting in a volume loss of 2.704 million m^3. In the archives of the Forest District of Comandău [37], it is mentioned that on the 1st of January 1996 (about two months after the windthrow from the 5th and 6th of November 1995), this phenomenon took place in all management units (eight in number). A total surface of 3884.70 hectares was affected and a volume of 605,790 m^3 was damaged.

In February 2020, the combined effect of wind, snow and low temperatures led to a surface of 1340.78 hectares being affected by windthrow in the Forest District of Comandău. Large-scale windthrow took place on a surface of 147.58 hectares and a wood volume of 52,273 m^3 was affected. In the rest of the area, that is, 1193.20 hectares, scattered windthrow took place which affected a volume of 24,280 m^3. The total volume affected amounted to 76,553 m^3, located in management units Bâsca Mare and Dealul Negru. An analysis of the two management units regarding the areas and the wood volume affected by the windthrow produced in 1995 and 2020 is presented in Table 1. The data from the table must not be regarded as a comparison between the two events but more like a warning that draws attention to the fact that the area under study is prone to windthrow.

Table 1. Analysis of the windthrow produced in 1995 and 2020 in management units Bâsca Mare and Dealul Negru.

	Year 1995 (November)			**Year 2020 (February)**		
Large-Scale or Scattered Windthrow	**Area Affected**	**Volume Affected**	**Intensity**	**Area Affected**	**Volume Affected**	**Intensity**
	ha (%)	**m^3 (%)**	**(m^3·ha^{-1})**	**ha (%)**	**m^3 (%)**	**m^3·ha^{-1}**
Management unit Bâsca Mare						
Large-scale windthrow	929.30 (98%)	383,139 (99.85%)	412.29	2.06 (1.34%)	569 (15.87 %)	276.21
Scattered windthrow	20.80 (2%)	567 (0.15%)	27.26	151.85 (98.66%)	3017 (84.13%)	19.87
Total 1	950.10 (90.62%)	383,706 (88.11%)	403.86	153.91 (11.48%)	3586 (4.68%)	23.30
Management unit Dealul Negru						
Large-scale windthrow	98.40 (100%)	51,801 (100%)	526.43	145.52 (12.26%)	51,704 (70.86%)	355.31
Scattered windthrow	-	-	-	1041.35 (87.74%)	21,263 (29.14%)	20.42
Total 2	98.40 (9.38%)	51,801 (11.89%)	526.43	1186.87 (88.52%)	72,967 (95.32%)	61.48
Total 1 + 2	1048.5 (100%)	435,507 (100%)	415.36	1340.78 (100%)	76,553 (100%)	57.10

In February 2020, in the management unit of Bâsca Mare, out of a total of 228 compartment units, two were affected by both scattered and large-scale windthrow, 19 were affected only by scattered windthrow and the rest of 209 compartment units remained unaffected. In the management unit of Dealul Negru, out of a total of 488 compartment units, 352 were not affected, 18 were affected by large-scale windthrow, 90 by scattered windthrow and 28 by both scattered and large-scale windthrow.

Out of the total surface affected, 9.92% was represented by areas where the entire compartment unit was affected with trees being blown down entirely (large-scale windthrow) while 90.08% was represented by areas where trees in the compartment unit were either blown down or snapped only in scattered placed (scattered windthrow).

In the management units, the total surface affected by windthrow represents approximately 15% for the management unit of Bâsca Mare and 51% for the management unit of Dealul Negru. As far as the volume affected is concerned, it amounted to 1% in the former case and 10% in the latter. Therefore, windthrow mainly took place in the management unit of Dealul Negru, both in terms of surface (88.52%) and volume (95.32%) affected.

The effect of windthrow and wind snap was a catastrophic one, given the huge volume affected (tens of thousands of m^3 in one event) [38] and their mark was devastating [39] both from the point of view of the surface and of the volume affected as the latter exceeds approximately three times the annual allowable cut.

In management unit Bâsca Mare, large-scale windthrow only took place in two tree stands. The limited amount of large-scale windthrow led to this not being included in this study.

Climatic conditions that led to windthrow, site conditions, characteristics of tree stands that affected and the extent of the damage were all analysed in this research.

Climatic data for the month of February 2020 were taken from the nearest weather station (Lăcăuți) situated at an altitude of 1777 m (Table 2).

Table 2. Climatic data for February 2020 (Lăcăuți weather station, Forest District of Comandău).

Day	Average Temperature (°C)	Precipitation Rate (mm)	Wind	
			Direction	Speed ($m \cdot s^{-1}$)
1	−1.7	1.0	West–Northwest	22
2	−0.7	0	West	25
3	−1.7	9.1	West	28
4	−3.1	14.9	West–Northwest	19
5	−6.7	4.2	North–Northeast	29
6	−14.1	0.0	N–NE	32
7	−11.7	1.6	West–Northwest	20
8	−14.7	0.0	Northwest	19
9	−8.7	0.0	West–Northwest	16
10	−4.2	0.0	West	23
11	−5.5	4.9	West	31
12	−8.0	0.0	West–Northwest	25
13	−8.4	0.0	West–Northwest	20
14	−6.8	0.0	West	16
15	−5.4	0.0	West–Northwest	12
16	−4.9	0.0	West–Northwest	17
17	4.2	0.0	West	12
18	1.6	0.0	West–Northwest	18
19	−2.7	0.0	West–Northwest	11
20	−5.0	0.0	Northwest	8
21	−6.4	0.0	West–Northwest	17
22	−7.3	0.0	West	16
23	−5.4	0.0	West–Northwest	24
24	−3.4	0.0	West	32
25	−3.0	0.0	West	22
26	1.7	0.0	West	18
27	−2.8	6.1	West	20
28	−7.2	6.0	West–Northwest	21
29	−7.3	8.2	West	13

The data on tree stand characteristics and site conditions were taken from the management plan of the Forest District of Comandău [40,41] and are presented in Tables 3 and 4.

Table 3. Tree stand structure characteristics.

Tree Stand Characteristics	Characteristics		Area Studied	
			ha	%
Tree stand origin	Artificial	Ps	220.44	6.61
		Pm	1137.02	34.09
		Pi	36.71	1.10
	Natural	Ps	390.74	11.71
		Pm	1485.28	44.53
		Pi	65.33	1.96
Age class	Class I (0–20 years)		771.27	23.12
	Class II (21–40 years)		326.44	9.79
	Class III (41–60 years)		702.53	21.06
	Class IV (61–80 years)		524.89	15.74
	Class V (81–100 years)		394.24	11.82
	Class VI (>101 years)		616.15	18.47
Tree stand structure	Even-aged stands		198.00	5.94
	Relatively even-aged stand		2429.59	72.84
	Relatively uneven-aged stand		707.93	21.22
Site class	II		611.18	18.32
	III		2622.30	78.62
	IV		102.04	3.06
Composition	Mixed stands		542.49	16.26
	Spruce pure stands		2793.03	83.74
Canopy cover	0.7–0.9		3233.35	96.94
	0.4–0.6		100.98	3.03
	0.1–0.3		1.19	0.04
Total area			3335.52	100

Note: Ps—high productivity, Pm—average productivity, Pi—low productivity.

Table 4. Site condition characteristics.

Site Conditions	Characteristics	Area Studied	
		ha	%
Relief unit	Plateau	7.68	0.23
	Slope	1960.21	58.77
	Lower slope	332.82	9.98
	Middle slope	543.25	16.29
	Upper slope	441.20	13.23
	High meadow	50.36	1.51
Land topography	Bumpy	3274.56	98.17
	Flat	60.96	1.83
Aspect	South; Southwest	768.25	23.03
	West; Southeast	1152.84	34.56
	Plane	58.04	1.74
	North; Northeast	605.26	18.15
	East; Northwest	751.13	22.52
Land inclination	<1°	51.67	1.55
	1–5°	6.37	0.20
	6–15°	355.99	10.67
	16–30°	2904.42	87.07
	31–50°	17.07	0.51

Table 4. *Cont.*

Site Conditions	Characteristics	Area Studied	
		ha	**%**
Altitude (m)	901–1000	2.24	0.07
	1001–1100	321.20	9.63
	1101–1200	194.67	5.84
	1201–1300	585.09	17.54
	1301–1400	838.67	25.14
	1401–1500	1040.09	31.18
	1501–1600	330.92	9.92
	1601–1700	22.64	0.68
Altitudinal plant layer	Spruce stands	1494.51	44.80
	Mixed stands	1841.1	55.20
Soil class	Cambisols	2338.23	70.10
	Protisoils	10.14	0.30
	Spodosols	966.21	28.97
	Histosols	20.94	0.63
Total area		3335.52	100

The next step was to analyse the combined effect of climate and site conditions, structural characteristics of tree stands and forest management in the area affected by the windthrow of February 2020.

Data Analysis

For the compartment units affected by windthrow, the intensity of windthrow ($m^3 \cdot ha^{-1}$) and the slenderness coefficient were calculated as the ratio of the average height to the average diameter of tree stands ($m \cdot cm^{-1}$). The analysis of the distribution of windthrow intensity was made individually for each management unit and separately for massive and scattered windthrow. The first step in the statistical analysis was to test the normal distribution of windthrow intensity using the Kolmogorov–Smirnov test (the KS test) (the XLSTAT version 2023.2.0.1411 was used) for a significance level of 5%. For normal distributions, by using ANOVA and multiple linear regression, statistical connections between windthrow intensity (dependent variable) and independent variable characteristics of tree stands (average tree stand height, slenderness coefficient, tree stand canopy cover, age, site class and tree stand structure) and of the land (altitude, aspect and ground inclination) were analysed. Regression significance was tested with the Fisher test (F) while the significance of the independent variable coefficients was tested using the t Student test for a level of significance of 5%, 1%, and 0.1%. For distributions other than the normal ones, the type of distribution was identified, the one that best describes the variation of windthrow intensity. The existence of correlations between windthrow intensity and the above-mentioned independent variables was tested by using Spearman rank correlation (Spearman's rho). The next step was to determine statistical indicators (mean, minimum and maximum values, standard deviation, and variation coefficient) of independent variables that influence the variation of windthrow intensity (Table 5).

Table 5. Statistical indicators of the dependent and independent variables studied.

Variable	Mean	Minimum	Maximum	Standard Deviation	Variation Coefficient (%)	Spearman's rho	p-Value
Management unit Bâsca Mare—scattered windthrow (number of tree stands: 19)							
Windthrow intensity ($m^3 \cdot ha^{-1}$)	31.19	5.73	95.58	21.49	68.89		
Stand height (m)	23.73	16.6	26.7	3.36	14.14		
Slenderness coefficient ($m \cdot cm^{-1}$)	0.70	0.50	1.01	0.12	16.54		
Canopy cover	0.74	0.60	0.90	0.08	10.33		
Age stand (years)	91.32	50	110	17.22	18.87		
Altitude (m)	1380	1100	1575	143.79	10.42		
Site class	2.89	2.00	4.00	0.46	15.85		
Aspect	3.16 (NV–V)	2 (N)	5 (SV)	-	38.44		
Land inclination (°)	22.16	12.00	30.00	4.27	19.28		
Stand structure	2.26	2.00	3.00	0.45	19.99		

Table 5. *Cont.*

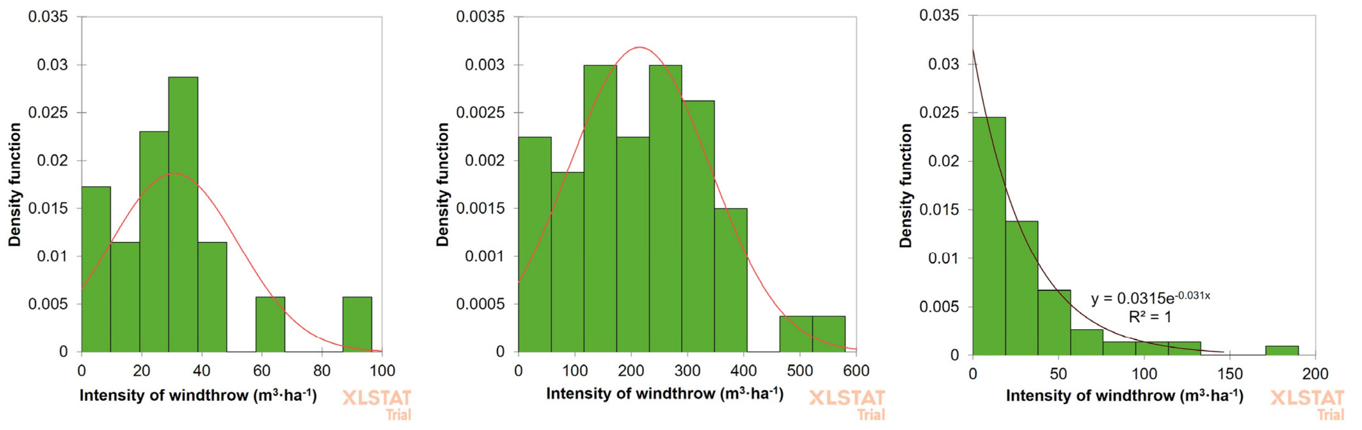
Variable	Mean	Minimum	Maximum	Standard Deviation	Variation Coefficient (%)	Spearman's rho	*p*-Value
Management unit Dealul Negru—large-scale windthrow (number of tree stands: 46)							
Windthrow intensity ($m^3 \cdot ha^{-1}$)	214.98	12.71	575.00	126.67	58.92		
Stand height (m)	24.39	16.20	29.2	2.99	12.26		
Slenderness coefficient ($m \cdot cm^{-1}$)	0.70	0.59	0.87	0.07	9.68		
Canopy cover	0.73	0.20	0.90	0.13	17.29		
Age stand (years)	90.87	50.00	130.00	22.64	24.91		
Altitude (m)	1396	1200	1555	94.88	6.80		
Site class	2.78	2.00	3.00	0.42	14.99		
Aspect	5.44 (SV–S)	2.00 (N)	9.00 (NE)	2.23	40.99		
Land inclination (°)	20.78	10.00	28.00	4.06	19.54		
Stand structure	2.17	1.00	3.00	0.57	26.21		
Management unit Dealul Negru—scattered windthrow (number of tree stands: 118)							
Windthrow intensity ($m^3 \cdot ha^{-1}$)	31.77	0.21	182.76	33.31	104.85	-	-
Stand height (m)	23.29	15.00	33.20	4.03	17.29	0.32	***
Slenderness coefficient ($m \cdot cm^{-1}$)	0.70	0.54	0.89	0.07	10.40	−0.30	**
Canopy cover	0.79	0.60	0.90	0.09	10.88	−0.39	***
Age stand (years)	86.27	40	135	25.42	29.47	0.28	**
Altitude (m)	1365	1150	1550	90.21	6.61	−0.09	>0.05
Site class	2.72	2.00	4.00	0.47	17.25	−0.20	*
Aspect	4.81 (SV)	2.00 (N)	9.00 (NE)	1.93	40.01	0.08	>0.05
Land inclination (°)	20.32	10.00	30.00	3.67	18.07	0.10	>0.05
Stand structure	2.11	1.00	3.00	0.50	23.82	−0.26	**

Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05.

3. Results

3.1. Statistical Data Interpretation

Statistical analysis has shown that in management unit Bâsca Mare, the variation of scattered windthrow intensity is normally distributed (KS test *p*-value = 0.545 > 0.05) (Figure 2a). By using multiple linear regression and by gradually eliminating independent variables for which no significant influence on the variation of windthrow intensity was statistically proven, the data presented in Table 6 were compiled. Among the independent variables, tree stand age is the one that best correlates with windthrow intensity. In fact, the only independent variable with which a strong positive correlation could be established was tree stand age ($r = 0.56$). In this situation, the coefficient of determination R^2 shows that the dependence of windthrow intensity on tree stand age is 32%, while 68% of the variation is caused by other factors.



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

Figure 2. Windthrow distribution: (**a**) scattered windthrow, normally distributed intensity (management unit Bâsca Mare); (**b**) large-scale windthrow, normally distributed intensity (management unit Dealul Negru); (**c**) scattered windthrow, exponentially distributed intensity (management unit Dealul Negru).

Table 6. Linear regression analysis of windthrow intensity in relation to tree stand age in management unit Bâsca Mare.

ANOVA				The Significance of the Variable Coefficient				
R^2	**Standard Error**	**Degrees of Freedom**	F	**Variable**	**Coefficient**	**Standard Error**	**t Statistic**	**p-Value**
0.32	18.20	Regression, 1 Residual, 17	8.08	Constant	−33.45	23.12	−1.44	-
				Tree stand age	0.71	0.25	2.84	*

Signification codes * < 0.05.

In management unit Dealul Negru, the variation of large-scale windthrow intensity is also normally distributed (KS test p-value = 0.89 > 0.05) (Figure 2b).

In the case of large-scale windthrow from management unit Dealul Negru, independent variables—land inclination and tree stand height—significantly and distinctly significantly influence the variation of windthrow intensity. There is a moderate correlation (r = 0.60) between the dependent variable and the independent variables, negative with ground inclination and positive with tree stand height. In this situation, ground inclination and tree stand height influence the variation of windthrow intensity in a proportion of 36%, with the other 64% of the variation being caused by other factors (Table 7).

Table 7. Linear regression analysis of windthrow intensity in relation to aspect and land inclination in management unit Dealul Negru.

ANOVA				The Significance of the Variable Coefficient				
R^2	**Standard Error**	**Degrees of Freedom**	F	**Variable**	**Coefficient**	**Standard Error**	**t Statistic**	**p-Value**
0.36	102.50	Regression, 2 Residual, 44	12.52 ***	Constant	−73.50	154.96	−0.47	-
				Land inclination	−9.71	3.76	−2.58	*
				Tree Stand height	20.18	5.09	3.97	***

Signification codes: 0 < *** < 0.001; 0.01 < * < 0.05.

Scattered windthrow has affected the highest number of tree stands in management unit Dealul Negru. As far as the variation of scattered windthrow intensity from management unit Dealul Negru is concerned, the KS test showed that the values of windthrow intensity do not follow normal distribution (KS test p-value < 0.0001). The same thing is indicated by the Shapiro–Wilk test (p-value < 0.0001). In the latter case, the variation of windthrow intensity follows an exponential function (Figure 2c). An analysis of the correlation between windthrow intensity and the independent variables taken into consideration was made by using the Spearman (r_s) nonparametric correlation coefficient. Thus, it was shown that, along with the statistical indicators of the variables studied (Table 5), the following moderate correlations exist: negative with the slenderness coefficient ($r_s = -0.30$), negative with canopy cover ($r_s = -0.39$) and positive with stand height ($r_s = 0.32$). Weak correlations exist with the following variables: tree stand age ($r_s = 0.28$), tree stand structure ($r_s = -0.26$) and site class ($r_s = -0.20$). No correlations were discovered to exist with the other independent variables studied—altitude, aspect and land inclination.

3.2. Climatic Conditions

According to meteorological data (Figure 3) and to observations made in the field, windthrow and snow break took place gradually in February 2020, strictly related to the speed and wind direction as follows:

(1) 2nd and 3rd of February, wind direction west, at a maximum speed of 28 m·s^{-1};
(2) 5th and 6th of February, wind direction north–northeast, at a maximum speed of 32 m·s^{-1};

(3) 11th and 12th of February, wind direction west–northwest, at a maximum speed of 31 m·s^{-1};
(4) 23rd and 24th of February, wind direction west–northwest, at a maximum speed of 32 m·s^{-1}.

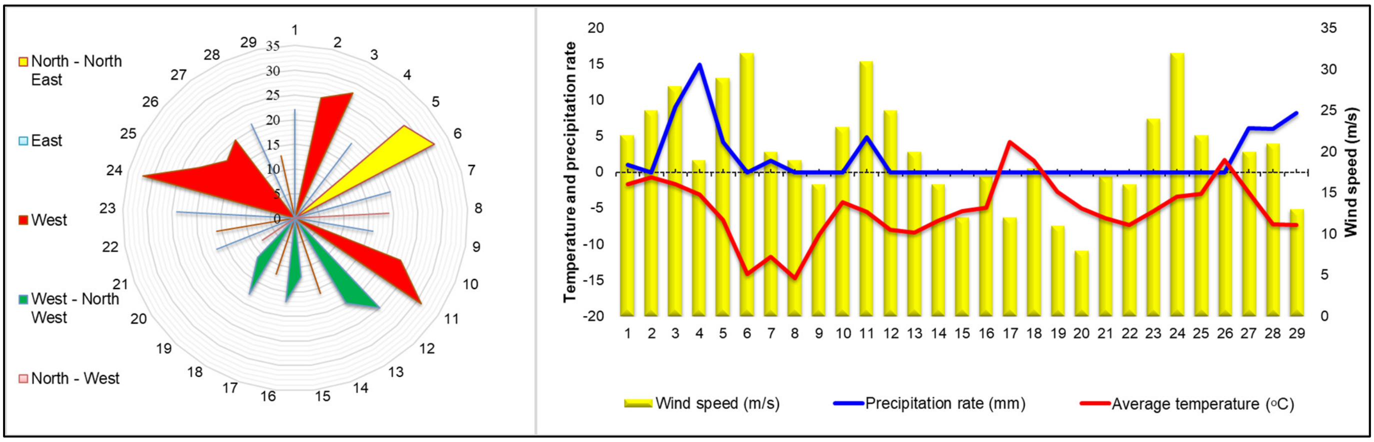


Figure 3. Wind direction and frequency in February 2020.

The movement of air masses from a direction different from the previously mentioned ones had a lower intensity, while windthrow was isolated without major implications with respect to tree stand structure.

Before the maximum impact of the windthrow from the 5th and 6th of February, the precipitation rate reached maximum values for that month, namely 14.9 mm on the 4th of February, while the average temperatures started to drop from −3.1 °C reaching values of −14.7 °C on the 8th of February. The time intervals between 11th and 12th of February and between 23rd and 24th of the same month were not preceded by a high precipitation rate and air temperature was close to the average temperature of February, that is, −5.1 °C. During these periods of time, given the destabilised tree stands where empty spaces occurred during the 5th and 6th of February, strong winds, coming from west–northwest, with a speed of 32 m·s^{-1}, similar to that of the currents from the north–northeast direction, caused scattered windthrow and contributed to an increase in affected surfaces.

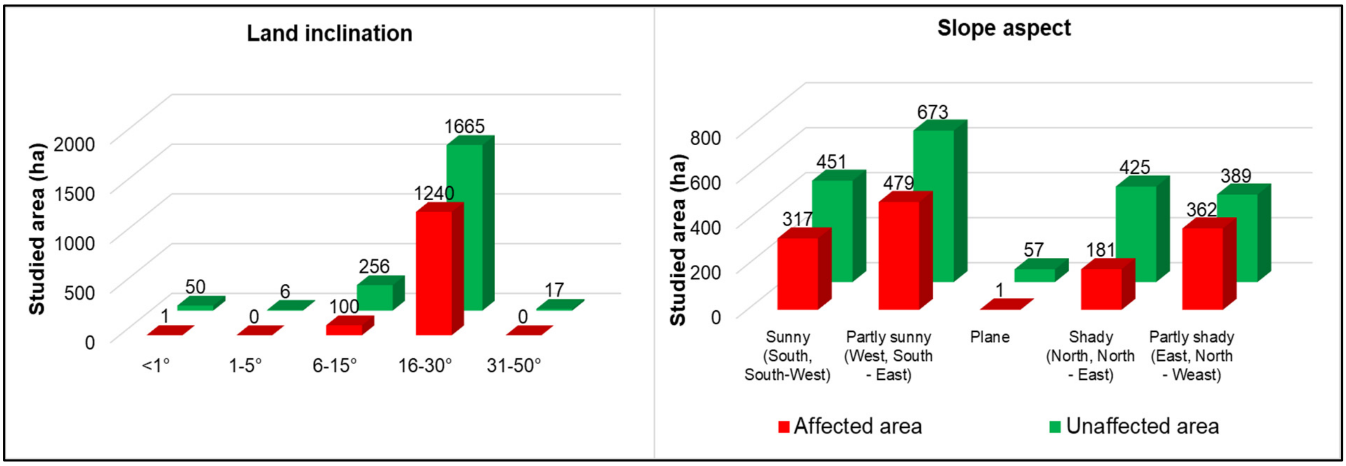
3.3. Site Conditions

In the area studied, the intensity of windthrow had the highest effect at slope level both in terms of the surface (65.66%) and of the volume affected (62.78%). This is due to the fact that this form of relief is representative of the area studied (58.77%).

Knowing the fact that the inclination of the ground significantly contributes to wind speed, it has been noticed that the most affected tree stands (93%) were the ones situated on slopes with an inclination ranging between 16° and 30°, followed by tree stands situated on slopes with an inclination between 6° and 15° (7%). No significant surfaces and volumes were recorded in tree stands situated on slopes with an inclination below 5° and over 31° (Figure 4a).

As far as slope aspect is concerned, windthrow occurred most frequently in partly sunny slopes (west, southeast)—35.76%—followed by partly shady slopes (east, northeast)—27.00%—sunny slopes (south, southwest)—23.68%—and shady (north, northeast)—13.47% (Figure 4b).

When analysing the way altitude influences windthrow, significant cases were registered between 1301 and 1500 m, an area of approximately 936.61 hectares and a volume of 62,371 m^3 being affected. Windthrow also caused effects between 901 and 1300 m and above 1500 m. However, these were less significant. High intensities of the phenomenon were registered in the area below the peak, on the ridge line between summit Zârna (1602 m)—summit Corobeți (1576 m)—summit Butuci (1516 m)—summit Poarta Vântului (1661 m)—summit Lăcăuți (1777 m)—summit Goru (1784 m) and summit Giurgiu (1723 m).



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

Figure 4. Distribution of surfaces affected by windthrow according to (**a**) land inclination; (**b**) slope aspect.

3.4. Tree Stand Structural Characteristics

Windthrow mainly affected fundamentally natural tree stands (79.48%) of low (1.50%), average (52.81%) and high (25.17%) productivity, but also artificial tree stands (20.52%), especially of average (19.44%) and high (1.08%) productivity.

As far as tree stand structure is concerned, even and relatively even tree stands were affected both from the point of view of surface (76.77%) and from the point of view of volume (74.04%).

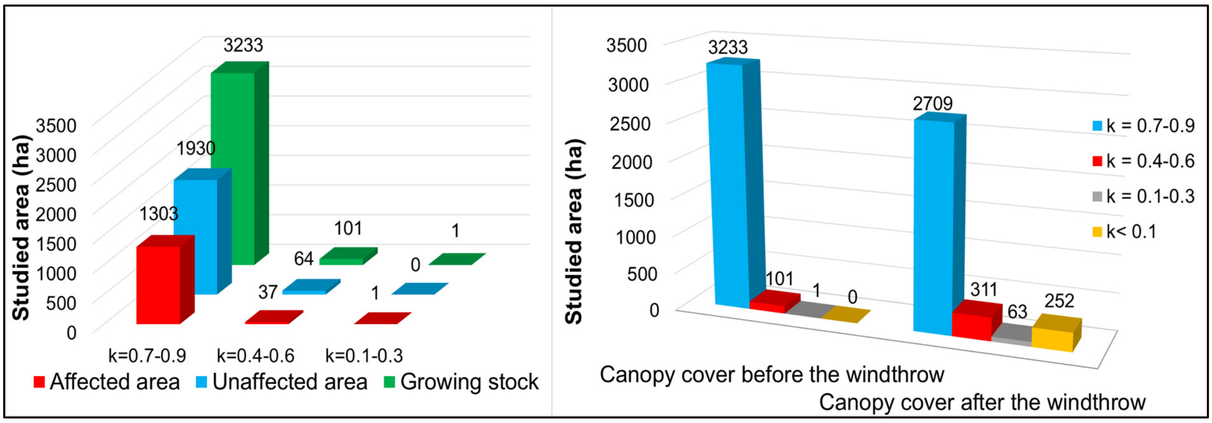
Windthrow affected tree stands from all age classes but mostly those aged above 40 years (98.92%).

In site Class III, the volume affected (76,553 m^3) represents 68.18%, while in site Class II, the volume affected amounts to 31.61%.

Research shows that 83.74% of the area studied is covered in pure spruce tree stands, while 16.26% is covered in mixed tree stands where spruce is the main species with a representation of 60%. This explains the severity of windthrow both in terms of surface and in terms of volume, these being mainly located in pure stands both in the case of large-scale windthrow (99.1%) and in the case of scattered windthrow (over 90%).

Before the windthrow took place, tree stands with an almost full canopy cover (0.7–0.9) were dominant (96.94%) in the areas studied. Canopy cover distribution is relatively uniform (Figure 5a) both in affected and unaffected areas. After the windthrow occurred, tree stands with an almost full canopy cover (0.7–0.9) amounted to about 81.23%, the difference being represented by tree stands where both scattered and large-scale windthrow took place (Figure 5b).

As far as the extent of the damage is concerned, approximately 51.59% of the tree stands in the studied area were not affected by this phenomenon. For 29.86% of tree stands, the damage was little (canopy cover was reduced by at most 0.1); for 7.10%, the damage was average (canopy cover was reduced by 0.1–0.2); for 3.66%, the damage was high (canopy cover was reduced by 0.3–0.5) and for 7.78%, the damage was very high (with a reduction in canopy cover of over 0.5).



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

Figure 5. Tree stand distribution according to canopy cover categories: (**a**) Comparative analysis of the canopy cover in affected and unaffected areas, before windthrow; (**b**) Comparative analysis of the canopy cover at growing stock level, before and after windthrow.

3.5. Anthropogenic Factors

In the management plans of units Dealul Negru and Bâsca Mare, it is mentioned that ever since 1948, silvicultural treatments have been performed. These included clear cutting in spruce stands, a uniform shelterwood system in beech stands and a group shelterwood system in mixed beech and spruce stands. The surface artificially regenerated in 1949 was of 743 hectares, and in 1958 it was about 123 hectares in the upper watershed of Bâsca river. Forests here were entirely harvested between 1950 and 1970. According to the same sources, the artificialisation of tree stands is the result of the use of extensive treatment (clear cutting) in the past, which makes these tree stands become more vulnerable to windthrow, wind snap and snow break. Therefore, without data regarding the management before 1949, it could be stated that, in the case of Bâsca watershed, the most important factor determining windthrow was the human one by the setting up of pure spruce stands in 1950, coupled with faulty thinnings (on about 17% of the area) between 1971 and 1982.

4. Discussions

Observations made in the Forest District of Comandău starting from 1960 onwards indicate that west and northwest wind directions are the dangerous ones, strongly affecting forests in this district. Also, a speed above 25 $m \cdot s^{-1}$ was registered several times between 1960 and 1964, resulting in serious damage. The Forest District archives show that "on the night of November, the 5th, 1995, a whirlwind occurred between 9 p.m. and 11 p.m. It caused large-scale windthrow with trees being blown down in the south–southwest direction. On the night between November the 5th and the 6th, 1995, the first snow in that year was recorded" [37]. Considering the layout of the blowdown trees, it can certainly be stated that the wind direction which led to this phenomenon was north–northeast. Between 1964 and 1966, in Romania, dangerous wind directions were identified to be north, northeast, northwest, west and southwest [42,43].

In Romania, similar observations show that climatic conditions characterised by a high precipitation rate, rain then sleet and snow, followed by an increase in air temperature and wind intensification, all coupled with relief characteristics, can become determining factors for the production of windthrow [34]. Likewise, in Switzerland, windthrow was attributed to an increase in temperature, precipitation rate and wind speed [44]. In Sweden, strong gusts of wind from north–northwest and north–northeast [45] were considered to be the cause of damage [18].

Land topography, ground inclination and aspect are relevant when analysing the risk of windthrow as they can either influence or compensate each other [46]. The role of relief in the occurrence of windthrow is crucial [47,48]. It represents the most important component of the active surface, which, by its characteristics and correlated with air circulation, favours the occurrence of windthrow [26]. Landform may increase or decrease wind speed and turbulence rate by deviating air currents and channelling them in a certain direction [46]. At the level of the studied area, large-scale windthrow occurred in watersheds where valleys are oriented in the direction of the wind. This is most likely due to air currents being channelled in a certain direction and to the uneven land [26,46]. In management unit Dealul Negru, a moderate negative correlation was only noticed in the interval of 10–28° where ground inclination influences windthrow intensity (p-value = 0.002). A correlation between windthrow intensity and aspect could not be statistically found in any of the cases analysed. Also, a statistical correlation between windthrow intensity and altitude could not be established in the cases analysed. The altitude was the independent variable with the lowest variation. In all cases analysed, the altitude variation coefficient is between 6.61% and 10.43%.

In Switzerland, similar studies conducted after cyclone Lothar and storm Vivian indicate that slopes with moderate inclination, exposed to wind and situated between 1200 and 1600 m, are more prone to significant windthrow [46].

From a phytoclimatic point of view, the areas studied are part of altitudinal layers, mixed tree stands (European beach and spruce) (44.81%) and pure spruce tree stands (55.19%). Pure spruce tree stands were more affected (62.47%). This was also the case in the period between 1960 and 1970 [42]. Wind mainly affects spruce tree stands and the severity of the damage increases as the productivity of tree stands becomes higher; the pure spruce tree stands are situated altitudinally closer to the mixed forest layer [48].

The most affected tree stands were situated on cambisols (74.85%) and spodosols (25.06%). Usually, the likelihood of damage increases with the decrease in root depth [49]. Over the years, a connection between soil characteristics and the risk of windthrow has been identified [46,50]. Soil texture and soil water regime normally influence the vertical development of roots by preventing fine root growth as a result of increased acidity or the lack of oxygen [51,52]. At the same time, soil characteristics are directly influenced by meteorological conditions, windthrow being a lot more frequent when soil is wet and not frozen [44].

Depending on provenance, structure, age, development stage, site class, composition and canopy cover, a tree stand can be considered vulnerable to wind or not [26,35,42,46,47,53–57]. A distinctly significant influence of tree stand structure (p-value = 0.005) on the variation of scattered windthrow intensity was found in management unit Dealul Negru where relatively even-aged tree stands are predominant.

Considering the fact that tree stands under the age of 40 are not seriously affected by windthrow, it could be stated that, until this age, trees grow sufficiently tall are capable of withstanding strong winds [45]. In the case of tree stands affected by large-scale windthrow, approximately 50% of the surface and volume affected are over 100 years old. The scattered windthrow is evenly distributed between ages 41 and 120 years old. Also, the volume affected per hectare is higher in age Classes V and VI (approximately 86.5 $m^3 \cdot ha^{-1}$) and it decreases with age: 42 $m^3 \cdot ha^{-1}$ in age Class IV and 22 $m^3 \cdot ha^{-1}$ in age Class III. Similar results have been reported in Sweden where pre-harvestable and harvestable tree stands have been observed to be more vulnerable to wind [55]. At the same time, tree stand vulnerability to wind is connected with the period of time that elapses since the last improvement cutting and the tree slenderness coefficient [51,58,59]. Thus, improvement cuttings can cause the weakening of the inner resistance of tree stands [1], making them more likely to be affected by wind for 2 to 10 years since the last intervention [60]. As far as tree stand age is concerned, it was shown that it correlates positively with scattered windthrow intensity in both management units analysed. The influence of tree stand age is significant in management unit Bâsca Mare (p-value = 0.011) and distinctly significant in management unit Dealul Negru (p-value = 0.002). Also, the slenderness coefficient distinctly significantly influences scattered windthrow from management unit Dealul Negru (p-value = 0.001).

Areas occupied by tree stands from site Classes III and II are extremely likely to be affected by wind. This can be explained by the fact that tree stands from superior site classes develop in site conditions which facilitate the achievement of tree slenderness coefficients above one, under circumstances of full or almost full canopy cover [48,61]. Data analysis showed that the average slenderness coefficient was 0.7 in all cases analysed, irrespective of the site class. In fact, the slenderness coefficient was 1.01 in just one tree stand from management unit Bâsca Mare. As far as the site class is concerned, this only influenced (p-value = 0.033) the variation of scattered windthrow from management unit Dealul Negru.

Normally, the stability of tree stands is related to their composition, the percentage of species that make up the stand, the stage of development and their density and structure [61]. The most affected forest types are pure spruce stands. One factor predicting this is the fact that during winter storms, wind action at the level of trees is higher in resinous trees than in broadleaves [62] because of the presence of the needles in the former which constitutes a barrier against wind. This, coupled with the shallow-rooted system, the characteristic of spruce trees, makes single spruce trees and spruce tree stands prone to being totally or partially uprooted. Similar studies show that tree stands where spruce is the dominant species are a lot more likely to be affected by windthrow than mixed tree stands. It is acknowledged that in mixed tree stands where broadleaves represent 25%–30% of the trees, the probability of windthrow and wind snap is about 50% smaller than in pure spruce tree stands [55].

Canopy cover can have a significant impact as it influences the shape of the stem and the air flux at stand level [63]. Thus, isolated trees, those from the forest edge or small ones, are more stable and can withstand wind better, whereas trees with large crowns and big heights are likely to be affected by wind action and speed [46]. Tree stands with a canopy cover below 0.6 are extremely concerning given the fact that they are the most fragile. It is to be expected that future storms mainly affect these tree stands. A moderate negative correlation was found to exist between the variation of scattered windthrow intensity from management unit Dealul Negru and the canopy cover of the stand, the latter influencing very significantly the variation of windthrow intensity (p-value < 0.001).

The complexity of windthrow can also be influenced by the health of tree stands. Healthy trees have a higher resistance to wind loads. Their resistance exceeds by 65% the resistance of unthrifty trees or trees with decayed roots [46]. A strong root system developed in direct proportion with tree height and crown density determines a higher stability of trees in the wind [46]. Another problem that has to be considered is the identification of interpopulation varieties (i.e., *Picea abies f. pendula*—spruce with a narrow crown) that resist better and adapt easier to wind and snow. Soil water content can also be an important factor that determines the stability of the tree. Trees adapted to moist soil are more stable [46].

The human factor contributes to the sustainable management of forest ecosystems, and it may influence the vulnerability of tree stands to windthrow, wind snap and snow break. The implementation of adequate strategies to optimise forest management is of the utmost importance [64]. With correct management, one can intervene and use improvement cuttings (thinning) at the level of tree stand structure in order to adjust stand composition, tree height and canopy cover. Moreover, even the development of the root system in the horizontal and vertical plane can be influenced [17,56,65,66]. Forest management, just as climate change, can contribute to increasing disruption [8]. The problem of windthrow and wind snap could benefit from the development of a mapping system of risk areas [33,38] at a local level, one that can show the relatively homogeneous direction of air currents. Given the multitude of factors that contribute to this phenomenon, mapping at a national level is not recommended. Moreover, the establishment of harvesting plans in high-risk areas as part of the management plan by including the estimated volume of windthrow would determine an even time and space distribution, and a more accurate one in terms of wood harvesting when responding to regeneration emergencies [38].

Taking into account the management plans of management units Dealul Negru and Bâsca Mare, it could be safely stated that the windthrow of 2020 was influenced by the anthropogenic factor starting from the setting up of the artificial pure spruce tree stands and continuing with the faulty management (failure to perform thinnings regularly). This was probably motivated by the lack of access to these watersheds until the beginning of the 1990s.

5. Conclusions

Previous research regarding the studied area showed that catastrophic windthrow occurred in the past as well. The most notable phenomenon took place in November 1995. The recurrent nature of windthrow is to be noted, with tree stands of the Forest District of Comandău being affected by scattered windthrow and wind snap either yearly or every two years.

The total surface affected by large-scale or scattered windthrow in February 2020 represents 40.20% at the level of the studied area and 7.38% in terms of the volume affected. Due to the fact that, as a result of this phenomenon, tree stands become more vulnerable, it is to be expected that they are affected more by biotic factors (insect attacks and fungi) but also by abiotic factors.

The maximum intensity of windthrow took place at a wind speed of 32 $m \cdot s^{-1}$ coming from north–northeast, the effect of windthrow being determined by the joint action of air currents from north–northeast and the air masses from west–northwest that acted occasionally. Pure spruce stands situated on slopes counter-placed to wind direction were mainly affected. The soils were mostly cambisols (Eutric cambisol and Dystric cambisols) and spodosols (podzol and pre-podzol) from the altitudinal layers of spruce stands and mixed stand.

Interaction between site factors, tree stand characteristics, as well as forest management and development decisions can contribute to the severity of windthrow, but it is difficult to quantify the exact contribution of each factor involved. This was proven by analysis and statistical interpretation of data, where, in the case of scattered and large-scale windthrow from the two management units, the same factors influence the variation of windthrow intensity differently or, what is more, in some cases, they either do not influence it at all or they can only account for a small part of this variation.

Tree stand management with the goal of reducing their vulnerability to windthrow is certainly a complex activity (selection of species, establishment of the planting scheme and composition and the planning of improvement cuttings) the result of which cannot be quantified or guaranteed. Windthrow and wind snap cannot be defined in terms of time and space, but based on site conditions, tree stand characteristics and historical data regarding the areas affected under certain climatic conditions, it can be stated that the studied area is prone to such phenomena.

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