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THE IMPACT OF EXTREME WEATHER PHENOMENA ON THE MANAGEMENT OF CONIFEROUS STANDS

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Abstract

Coniferous stands are relatively vulnerable to the impact of extreme weather events, often being affected by windfalls, because the spruce species (Picea abies L.) has a trailing root system. As a result, high-intensity winds cause windfalls on compact surfaces and the breaking of tree crowns and trunks. Windfalls in spruce stands also affect the forest soil, on considerable surfaces. The case study was carried out in spruce stands in the Horea Apuseni Forest District, Alba County, which were affected by windfalls and breakages. The objectives of the case study refer to the impact of the extreme weather events of 2011-2017 on spruce stands, forest soil and implicitly on the management of the affected forest unit. The wood affected by these extreme phenomena was valued at a price specific to the assortments and quality of accidental wood products, registering considerable financial losses. Also, a microrelief specific to wind fellings was formed, with a extremely negative impact on the ecological rehabilitation process of the affected spruce stands. The regeneration process of these stands was carried out over a relatively long period, 10-12 years, with very large financial efforts

Key words: *extreme weather events, spruce stands, forest soil, accidental wood products, ecological rehabilitation.*

INTRODUCTION

Spruce-dominated coniferous stands in mountainous areas are highly susceptible to windthrows and windbreaks caused by extreme weather events.

In recent years, the frequency of extreme weather events has increased, and as a result/ thus, their effects have significantly influenced the stability of spruces. As a result, spruce stands in the stages of youth and maturity, which are characterized by relatively high thickness and density, are relatively vulnerable to windthrows and windbreaks.

The increasingly evident emphasis of climate change exerts a direct influence on the frequencies and intensities of extreme weather events in areas covered with forest vegetation in Europe. As a result, major issues have been reported in spruce (*Picea abies* L. Karst) stands.

Although they are considered some of the most important forest formations in Northern Europe, in terms of ecological and economic importance, they present a high vulnerability to the action of strong dominated winds (Krišans et al., 2020). Because the spruce species has a trailing root system, uprooting and felling caused by potentially destabilizing environmental factors, such as strong winds, high-intensity storms, heavy rainfall, and especially combinations thereof, are frequently reported (Figure 1) (Cristea, 2004).

Figure 1. Root system of a windthrown spruce tree (Crainic, G. C., 25.07.2011, plot 80A, Production Unit I Vadul Moţilor, Horea Apuseni Forest District, Alba County)

The image in Figure 1 indicates that the windthrown spruce specimen has a superficial root system, with roots developed horizontally and without a distinct central taproot.
As a result, the cause of the low degree of ecosystem stability of spruce stands to the destabilizing action of high-intensity winds is due to the architecture of the spruce roots, which is essential for their anchoring in the soil and their stability. In well-drained and deep soils, spruce roots develop optimally, and the volume of the root system, consisting of roots and soil, is large, ensuring high anchoring and stability. Consequently, on shallower soils, with rock relatively to the surface, the volume of tree root systems is reduced, and the anchoring and stability of trees is considerably reduced (Krišans et al., 2020).

Figure 2. Spruce stand in plot 83A, affected by windthrow and windbreak (Crainic, G. C., July 25, 2011, Production Unit I Vadul Moţilor, Horea Apuseni Forest District, Alba County)

Climate change is recognized as one of the biggest problems the world is facing nowadays, representing a potential threat to the environment (Psistaki et al., 2024). These favor and trigger a series of extreme weather phenomena, which represent major stress and destabilization factors for forest ecosystems, causing both immediate and long-term effects (Barbagallo et al., 2024).
Windthrows and windbreaks, as direct effects of extreme weather events, cause major changes in the growth, development and evolution of coniferous stands. In this context, both isolated trees and compact stands are affected, with a particularly strong ecological, social and economic impact.
In Romania, in recent years, a series of windthrows and windbreaks have been reported in spruce stands. These events impacted large areas of spruce forests in the Apuseni Carpathians during July 2011 (Figure 2) and September 2017, affecting stands at multiple developmental stages (Crainic et al., 2024).
Exploitable stands were also affected, on various areas in the Curvature Carpathians (a transitional zone between the Eastern and Southern Carpathians of Romania) in February 2020, such as the upper basin of the Bâsca River where large-scale windfalls were recorded in 1995 (Ciocirlan & Câmpu, 2024).
Recent research conducted in the Curvature Carpathians, mainly pure spruce stands, located on land with a slope between 16 and 30°, highlights the fact that the impact of extreme weather phenomena had a maximum intensity when the wind came from the north - northeast direction, and reached a maximum speed of 32 m/s (Ciocîrlan & Câmpu, 2024).
In recent decades, windthrows and windbreaks, followed by bark beetle infestations, represented by the species *Ips typographus* L. in softwood stands, have caused widespread disturbances in forest ecosystems. As a result, the Earth's carbon balance has been significantly affected, modifying soil respiration, with direct implications for the decrease in gross primary productivity in the affected stands (Bozzini et al., 2023; Tomes et al., 2024).
Dead wood from trees affected by extreme weather events influences the increase in soil heterogeneity, due to the formation of a specific microrelief due to windfalls (Geambaşu, 1984; Kikeeva et al., 2024). A series of soil properties are also determined by the physical and chemical characteristics of wood during its decomposition, under the direct influence of environmental conditions and

microorganisms in forest ecosystems (Sicoe et al., 2023; Kikeeva et al., 2024).

Recent studies confirm that fallen spruce logs, in moderate and advanced stages of degradation, have a direct influence on the horizontal distribution and heterogeneity of the soil cover with herbaceous and shrub species, in the area bordering them. Consequently, dead spruce wood influences the coverage of the bordering areas with acidophilic and slightly acidophilic species. It was also found that the impact of wood in different stages of decomposition on soil heterogeneity parameters can be traced up to 20 cm from the tree (Kikeeva et al., 2024). Storms in recent years have also affected the stands of conifers of the *Pinus halepensis* and *Pinus sylvestris* species in the Mediterranean forest area. Their effects on soil characteristics were evident, as a result of which the percentage of clay increased in the gaps where the trees were felled, and the value of the concentrations of the elements K and Mg decreased. As a consequence, especially the soil surfaces that were affected by the destruction of the *Pinus halepensis* stands became less fertile, being dominated by species of bacteria specific to the new conditions created (Camarero et al., 2021).

Studies conducted in balsam fir - *Abies balsamea* (L.) Mill stands, which grow over large areas in Quebec and are very vulnerable to the impact of strong winds, highlight their differentiated stability, depending on the growing season, season and the specific climatic elements, especially precipitation. As a result, the moment of recovery from bending of balsam fir trees (*Abies balsamea)* is relatively greater in winter than in summer (during the growing season) for the same characteristics of the dominant wind (Duperat et al., 2020).

Although harsh winter conditions, with low temperatures and heavy snow, are considered to pose an additional risk to the stability of trees and, implicitly, of the branches, the increase in the resistance and rigidity of the stem and root system during freezing temperatures and the change in wind flow through the forest, due to snow on the canopy and on the ground during this period, is evident (Duperat et al., 2020).

There are cases where windthrows and windbreaks can significantly interfere with management practices applied in some forest ecosystems. In situations where the impact of extreme weather events is frequently reported, without any human intervention, management and regeneration cutting of stands carried out without adequate management for the respective seasonal conditions, can lead to an increase in the ecosystem instability of the respective stands (Ruel, 2020). As a result, a series of concerns are currently being reported for promoting a management of forest ecosystems using natural disturbances related to their stability (Ruel, 2020). It is obvious to promote an adaptive management for this particular situations which are in many cases even extreme (Pomara & Lee, 2021).

Adopting a management approach, that has as its main objective the minimization of damage induced by strong wind storms in various forest ecosystems, can be based on the knowledge and results obtained from the vast research and studies carried out to date in this field. Consequently, the use of complex management templates, obtained based on the simulation of the conditions for facilitating and achieving fellings and ruptures caused by strong prevailing winds, can be successfully exploited for the design of optimal strategies for sustainable management of forest resources (Ruel, 2020).

The use of wind damage prediction and simulation models, such as ForestGALES_BC, for a series of boreal stands in North America, for both normal and extreme wind speeds, has made it possible to create the premises for adopting optimal decisions and strategies regarding risk management and planning for competitive forest management (Anyomi et al., 2017). The results of the simulations in the studied stands present the following three scenarios:

- at a wind speed of 5 m/s, the estimated amount of felling varied from 0 to 20% of the area;
- for winds with a speed of 20 m/s, the damage increased to 2 to 90% of the area;
- for winds of 40 m/s, the damage varied from 10 to 100% of the area (Anyomi et al., 2017).

The area affected by windthrows, and respectively their intensity, varied depending on the type of stands. As a result, the stands that present high ecosystem stability are those represented by deciduous, hard-core species (Anyomi et al., 2017).

The genetic diversity of tree populations is one of the most important factors determining the stability and sustainability of forest ecosystems. The results of recent studies on the possible changes in the genetic diversity of naturally regenerating populations of spruce and Scots pine in various habitats indicate that a pronounced genetic diversity in regenerating populations provides a basis for the formation of stands capable of adapting to constantly changing climatic conditions (Verbylaite et al., 2017).

Naturally regenerated spruce and Scots pine seedlings, which were randomly analyzed from a spatial point of view, presented the same genetic diversity as the presumed maternal populations. Therefore, the genetic differentiation between trees from maternal populations and the naturally regenerated seedlings from them was low for the two species. More than this, information about the genetic dynamics of natural populations of Scots pine and spruce species that were studied may be important for the analysis and assessment of possible changes in genetic diversity at a local scale, which were induced by the disturbance of ecosystem stability and the interruption of the climax state and, respectively, by the modification of vegetation conditions in the new habitats related to the stands on which they were established (Verbylaite et al., 2017).

The variability in site conditions, genetic diversity of coniferous stands, and the forest management strategies employed are key factors in enhancing stand resilience to extreme weather events.

The solutions proposed by current forest strategies, to protect and promote ecosystem services and biodiversity, require a deep understanding of how global climate change will affect the dynamics and processes in forest ecosystems (Girona et al., 2023).

MATERIALS AND METHODS

This case study was conducted in nine coniferous stands within Production Unit I Vadul Moţilor, managed by the Horea Apuseni R.A. Forest District in Alba County (Figure 3), which were severely impacted by windthrows and breakages resulting from the extreme weather event of July 20, 2011.

Figure 3. Case study location
(https://www.google.com/search...;
https://www.comune.ro/?/judet/ijud1/.;
https://earth.google.com/web/search/Cabana...)

The objective of this study is to analyze the impact of the July 20, 2011 extreme weather event on the management of coniferous stands severely affected by windthrows and windbreaks.

Field surveys were conducted to identify the affected stands, followed by stationary observations to determine the specific interventions required for their rehabilitation.

The experiment involved a complete inventory of the affected trees and the implementation of ecological rehabilitation measures.

Since the studied stands were entirely affected by windthrow and windbreak, for the quantitative-and implicitly, economic-assessment of the damaged timber, the technical regulations in force within the forestry sector and the Forest Code require a complete inventory of these areas.

All trees affected by the extreme weather event of July 20, 2011, were inventoried, and their volumes were calculated using the SUMAL 1.0 software. The economic value of the assessed timber was determined in accordance with the legal regulations in force at that time.

To study the factors and conditions that contributed to the occurrence of windbreak and windthrow events, elements of the forest site were analyzed, specifically the vegetation conditions and the characteristics of the forest vegetation. For the studied stands, the corresponding forest management plan was analyzed in detail, in parallel with field observations.

Rehabilitation efforts included the removal of harvesting residues, completion of regeneration through planting, and the management of mixed stands until they reached a closed-canopy (massif) condition. Materials used for the study included the project and management map of Production Unit I Vadul Moţilor (Horea Apuseni Forest District, Alba County), accounting records, forestry work contracts, relevant technical regulations, and specialized software for the quantitative and economic evaluation of the damaged timber.

RESULTS AND DISCUSSIONS

Analysis of the seasonal and vegetation conditions of the affected stands, summarized in Table 2, revealed that all plots shared similar stand types, soils, and forest classifications. The average elevation ranged from 1,300 to 1,475 meters, while slope gradients varied between 12 and 23. According to Figure 4, 34% of the plots faced east, 33% north, 22% southwest, and 11% northeast, indicating two predominant and two intermediate exposure types (Table 2). Most affected plots were located on undulating slopes in a proportion of 89% and the undulating upper slope in a proportion of 11% (Table 6).

Regarding the composition of the affected stands, 45% are almost pure, 44% are mixed and 10% are pure (Figure 7 and Table 2).

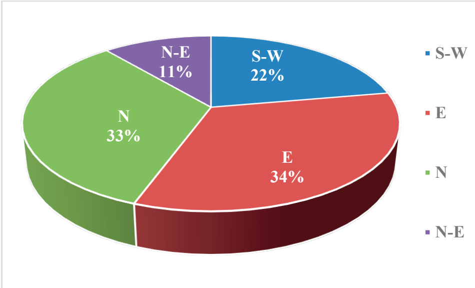

Figure 4. Distribution of affected plots according to exposure

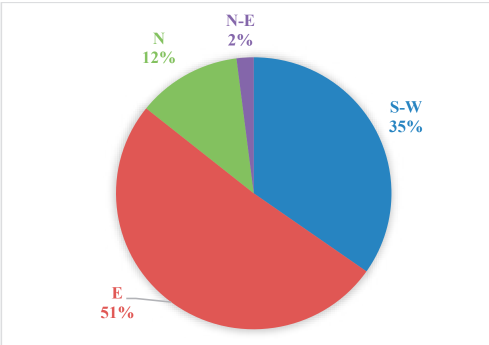

Figure 5. Volume distribution of affected trees by stands exposure

According to the results shown in the diagrams in Figures 4 and 5, the NE exposure accounts for 11% of the surface area of the affected stands, while the volume of affected trees in stands with this exposure represents 2% of the total volume.

Based on field observations, the direction in which the trees were windthrown is NE-in areas shaped like parallel strips. Consequently, the wind that caused the damage blew with high intensity from this direction.

Recent studies on spruce stands in two management units within the Curvature Carpathians - located opposite to the prevailing wind direction and situated at elevations between 1,300 and 1,500 meters on cambisols and spodosols - have yielded differing results. The same environmental factors were found to influence the intensity of windthrows and breakages inconsistently, with some factors proving statistically insignificant or relevant to only a small portion of the observed variation (Ciocîrlan & Câmpu, 2024).

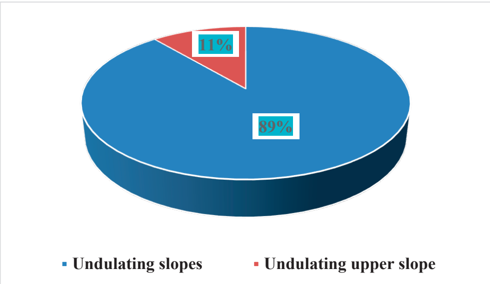

Figure 6. Distribution of affected plots according to landform

Consequently, based on current research and considering recent climate change trends, it remains challenging to accurately determine the relative contribution of predisposing factors and immediate triggers to wind-induced fellings and breakages across the studied stands.
As a consequence, it is relatively difficult to accurately determine the proportion of predisposing and triggering factors responsible for windthrow and windbreak in the studied areas based on the analysis of research conducted in stands affected by extreme weather events - both coniferous and broadleaved - within Production Unit (P.U.) VII Văratec, Sudrigiu Forest District, Bihor Forest Directorate, from 2017 to the present (Research contract no. 9, 19.07.2019), and considering the trend of climate changes in recent years.
Following the analysis of the affected stands and the complete inventory of windthrown and broken trees, the presence of accidental wood products was confirmed.
Given that the age of these stands exceeded half of their exploitable rotation age, the resulting timber was classified as 'Accidental I' products (Figure 8).
In accordance with current forestry regulations, such products are assimilated to the main wood harvest and are therefore deducted from the allowable cut volume established in the existing forest management plan (Paluš et al., 2020; Law 331/2024 Forestry Code, 2025).
After processing the field data, the values related to the volumes for each plot were obtained. The total volume of trees inventoried and considered as accidental products I, in the nine affected stands, is 28,466 m^3, on an area of 147.30 ha (Table 1). The market price was primarily influenced by wood quality, which declined significantly due to damage from windthrows and windbreaks (Figure 9a).

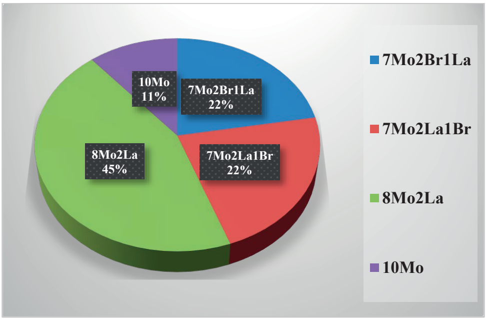

Figure 7. Distribution of affected plots according to the target composition of the stands

Table 1. Volume of trees felled and broken by the wind, in the affected stands

Forest plot	Surface (ha)		Affected volume (m^3)		Percent age of damage (%)
	The total	Affect	Total	per hectare	
63A	27.90	27.90	7,202	258.136	100
64A	19.70	19.70	2,687	136.396	100
80A	38.50	38.50	9,092	236.156	100
81A	17.00	17.00	492	28.941	100
83B	17.30	17.30	4,933	285.145	100
84B	1.90	1.90	571	300.526	100
85A%	35.60	3.40	335	98.529	9.55
85B	11.50	11.50	2,417	210.174	100
86B	10.10	10.10	737	72.970	100
Total	**179.50**	**147.30**	**28,466**	**193.252**	**82.06**

Ecological rehabilitation of the affected stands involved a range of targeted interventions (Govedar et al., 2018; Research contract no. 9 19 07 2019). The use of tree species for the regeneration of wind-damaged stands must ensure increased ecosystem stability. As a result, the compositions used must be made up of tree species with ecological behavior adapted to environmental conditions in areas vulnerable to the effects of extreme weather phenomena, in order to ensure consolidated ecosystem stability (Ikonen et al., 2020; Konôpka et al., 2021).

Priority was given to promoting biogroups of naturally regenerated spruce, established effectively through wind-assisted seed dispersal (Figure 8). As a result, natural regeneration was successfully achieved on a total area of 57.10 hectares (Table 4), in the upper part of the slopes, bordering the unaffected stands, which produced abundant fruit during the period 2011-2014. In areas where natural regeneration did not occur, reforestation was implemented through staged artificial planting, using species-specific approaches tailored to site conditions.

Table 2. Seasonal and vegetation conditions in affected stands

Forest plot	S (ha)	Foret site	Type forest	Soil	Relief	Exposition	Declivity	Altitude	Flora indicators	Stand Structure	Stand Composition
63A	27.90	2312*	1121**	4101***	undulated slope	S-W	20	1300	*Hylocomium splendens*	even-aged stand	7Mo2Br1La
64A	19.70	2312	1121	4101	undulated slope	S-W	18	1350	*Hylocomium splendens*	even-aged stand	7Mo2La1Br
80A	38.50	2312	1121	4101	undulated slope	E	15	1375	*Hylocomium splendens*	even-aged stand	7Mo2Br1La
81A	17.00	2312	1121	4101	upper side slope	E	12	1475	*Hylocomium splendens*	even-aged stand	7Mo2La1Br
83B	17.30	2312	1121	4101	undulated slope	E	22	1325	*Hylocomium splendens*	even-aged stand	8Mo2La
84B	1.90	2312	1121	4101	undulated slope	N-E	23	1300	*Hylocomium splendens*	even-aged stand	8Mo2La
85A%	35.60	2312	1121	4101	undulated slope	N	18	1325	*Hylocomium splendens*	relativ even-aged stand	10Mo
85B	11.50	2312	1121	4101	undulated slope	N	18	1325	*Hylocomium splendens*	even-aged stand	8Mo2La
86B	10.10	2312	1121	4101	undulated slope	N	18	1350	*Hylocomium splendens*	even-aged stand	8Mo2La

*2312 - The phytoclimatic layer of Mountain spruce forests, of medium quality, with brown podzolic-brown podzol soil, with medium - submedium edaphic volume, with *Hylocomium splendens*; **1121 - Spruce forest type, with green mosses - *Hylocomium splendens*, of medium productivity; ***4101 - Typical brown alluvial soil; Mo - spruce species, Br - fir species, La - larch species, S-W -South-West, E – East, N-E -North East, N-North.

Figure 8. Trees broken and felled following extreme weather events, in the stand of plot 63 A (G. C. Crainic, July 25, 2011, Production Unit I Vadul Moţilor, Horea Apuseni Forest District, Alba County)

The artificial regeneration process involved a series of specific forestry operations, including the following technical works:

- C1IIIb - clearing land in preparation for afforestation;
- C21.a+b1 - developing or redeveloping storage glaciers for seedlings;
- C20IIb3 - excavating trenches for seedling storage;
- C23Ic12 - transporting seedlings by manual carrying;
- C24Ia1 + C24IIa - storing seedlings in trenches and preserving them in glaciers;
- C70Ic - planting seedlings in planting spots on unprepared land designated for reforestation;
- C70Ic - planting seedlings in hearths in unprepared land, in lands intended for reforestation.

In areas where incidental wood products had been harvested and natural regeneration did not occur; it was necessary to mitigate the negative impacts of logging.

To ensure optimal conditions for artificial reforestation, logging residues and abandoned wood - primarily from broken trees - were collected and deposited in uprooting cavities and small clearings (Figure 9a). Stages of carrying out regeneration and maintenance works on areas where accidental products have been harvested are suggestively illustrated in the images in Figure 9.

a) Wood material to be removed from natural regeneration biogroups of spruce species, in plot 85B (G.C. Crainic, 03.04.2014, Production Unit I Vadul Moţilor)

b) Successful definitive mixed regeneration of spruce, in plot 63A (G.C. Crainic, April 11, 2025, Production Unit I Vadul Moţilor)

c) Bare-rooted seedlings of spruce, fir and larch species, kept in the trench, on the day they were planted, in plot 64A (G.C. Crainic, 05.04.2014, Production Unit I Vadul Moţilor)

d) Removal of overwhelming shrub and herbaceous vegetation, mechanized, from coniferous sapling biogroups, in plot 85B (G.C. Crainic, 05.11.2014, Production Unit I Vadul Moţilor)

Figure 9. Stages of establishing and managing (maintaining) natural and mixed regenerations in the affected stands of Production Unit I Vadul Moţilor

Table 3. The market value of wood assessed in the affected plots, in 2011

Forest plot	Average selling price		Total amount	
	RON/m³	EURO/m³	RON	EURO
63A	180	42.00	1296360	302484,00
64A	180	42.00	483660	112854,00
80A	180	42.00	1636560	381864,00
81A	105	24.50	51660	12054,00
83B	180	42.00	887940	207186,00
84B	180	42.00	102780	23982,00
85A%	105	24.50	35175	8207,50
85B	105	24.50	253785	59216,50
86B	105	24.50	77385	18056,50
Total	**Average price**		**4825305**	**1125904,50**
	169.51	**39.55**		

Much of the wood, particularly from visibly damaged or weakened trees, was left in various parts of the impacted plots. As a result, this aspect affected the health of the neighboring stands and, respectively, of the future mixed regenerations that were established between 2012 and 2024.

Consequently, in the spring of 2015, an attack of the spruce sapling borer - *Hylobius abietis* L. on spruce saplings, artificially regenerated (Figure 10).

Figure 10. Attack of the species *Hylobius abietis* L. on spruce seedlings, in artificial regenerations in the affected plots (G.C. Crainic, 03.04.2014, plot 84B, Production Unit I Vadul Moţilor)

To prevent these pests, poisoned baits were used, made from fresh spruce bark that had been treated with insecticide (Figure 11). As a result, the effects of the attack were limited to an area of 2.00 hectares, on which the regeneration of the spruce species was completely compromised.

Another consequence of maintaining considerable quantities of wood in the affected plots was the reduction of the area on which it was necessary to establish forest vegetation in the following decade.

Bare-rooted seedlings of spruce, fir and larch species were planted on an area of 90.20 hectares (Table 4). The number of seedlings planted per hectare was 5000, which were arranged in a rectangular arrangement (in the corners of a rectangle), at 1 m per row and 2 m between rows.

The saplings used for the afforestation works were purchased by the owner of the forest fund, respecting their area of origin.

Figure 11. Combating the attack of the *Hylobius abietis* L. species with poisoned baits, made from fresh spruce bark, which has been treated with insecticides (G.C. Crainic, 03.04 .2014, plot 84B, Production Unit I Vadul Moţilor)

Table 4. Evidence of areas that have been naturally and artificially regenerated in the affected plots

Forest plot			
Number	**Regenerated surface (ha)**		**Species used**
	Natural	**Artificial**	
63A	11.40	16.50	spruce, fir and larch
64A	5.90	13.80	
80A	27.00	11.50	
81A	0.00	17.00	
83B	0.00	17.30	spruce and larch
84B	0.00	1.90	
85A%	2.50	0.90	spruce
85B	5.40	6.10	spruce and larch
86B	4.90	5.20	
Total	**57.10**	**90.20**	-

Until they were transported to the plantation site, the saplings were kept on the ice, in optimal conditions, in accordance with the technical regulations in force. On the day they were planted, they were transported and stored in the ditch, in the afforestation site, with the

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roots covered with soil to protect them from degradation (Figure 9c).

Biogroups of larch seedlings were placed on the areas exposed to the wind (Figure 12), fir seedlings were planted in the wetter, relatively shaded portions, and spruce seedlings were planted on the surface difference (Figure 13).

The works necessary for the management of natural and artificial regenerations until the achievement of the under-canopy stage were represented by:

- completion of regeneration through plantations of bare-root seedlings of spruce, fir and larch species;
- C58Ib-clearing of forest species of grassy, shrub and woody species over the entire surface;
- C58IIb3-clearing of forest species of grassy, shrub and woody species around the seedlings;
- C46c-review of natural regenerations and plantations.

Figure 12. Larch seedlings planted in an area exposed to the wind, in plot 86B (G.C. Crainic, 03.04 .2014, Production Unit I Vadul Moţilor)

The work to complete the natural and artificial regeneration was carried out by planting bare-root saplings on the areas where it is missing on an area greater than 9 m^2 (Figure 14). The working technique is similar to that of integral plantations. Consequently, completions were carried out with saplings of the three previously mentioned coniferous species.

The excessive grassy, shrubby, and woody vegetation around the spruce sapling groups, which were established naturally and artificially, was removed was carried out manually and mechanized with power tools with cutting discs (Figure 9d), as appropriate.

These works were carried out towards the end of the vegetation season, starting on September 15, for reasons that depend on the evolution of the climate in the mountainous areas, but equally on local experience.

Figure 13. Spruce seedlings planted in an area without natural regeneration, in plot 85B (G.C. Crainic, 03.04.2014, Production Unit I Vadul Moţilor)

The works to review the natural and artificial regeneration aimed to remove the remains of grassy, shrubby and woody vegetation from the saplings, after the snow melted, and bring them to a vertical position. During these works, all the surfaces undergoing regeneration were covered, and these were effectively carried out only in the areas where the saplings were affected.

The achievement of the under-canopy state for natural and artificial regeneration on the surface of the affected plots was carried out in successive stages, during the period 2014-2024, due to the climatic conditions in this interval.

In accordance with Order no. 2537 of September 28, 2022, the under-canopy state for natural regeneration of coniferous trees is considered achieved when the height of the seedlings is 1.00-1.20 m, and in artificial regenerations the height of the seedlings varies between 1.20-1.40 m (Figure 9b).

Consequently, work was necessary to complete the regeneration in considerable areas, due to high temperatures and lack of precipitation during the vegetation season. These climatic elements were the main limiting factors that conditioned the final success of the established silvicultural crops.

Figure 14. Spruce saplings, planted during the regeneration completion works, to protect a stump (G.C. Crainic, 03.04 .2014, Production Unit I Vadul Moţilor)

All works carried out between 2012 and 2024 were considered investment works and were financed from the conservation fund, which was set up in the amount of 25% of the total value of the incidental wood products I, considered as main products, from the affected plots. Therefore, the conservation fund corresponding to the volume of wood recovered is 1,206,326.25 ron, the equivalent of 281,476.13 euro.

The recovery of spruce wood from the affected plots at an average price of 169.51 lei/m^3, or the equivalent of 39.55 euros/m^3, was carried out under extreme conditions, given its quality (Figure 8). If the price of the softwood wood is considered, obtained from main products, it is found that it has at least double the value compared to that of accidental products I. It is also found that the wood from the affected plots was recovered at a lower price, thus registering a consistent economic loss.

Recent studies conducted in Italy have also highlighted that following the storm in 2018, in the Upper Valtellina area, during the period 2019-2020, losses due to wood destruction were recorded, amounting to 5.10 million euros for the Valdisotto location, 0.32 million euros for Valfurva and 0.43 million euros for Sondalo, respectively. These losses were also added to those caused by the lack of carbon sequestration on the affected areas (Barbagallo et al., 2024).

Although the high diversity of tree species cannot necessarily cushion the economic consequences due to extreme weather phenomena (Fuchs et al., 2024), it nevertheless constitutes a factor of stability in spruce stands in the mountain area.

To promote an adaptive forest management, it is necessary to consider the concept of expected loss. This is an appropriate measure for integrating risk when establishing tree species and determining the optimal period of the production cycle (Möllmann & Möhring, 2017).

An alternative (differentiated) forest management can provide a specific value of resilience to storm adaptations. As a result, the specific goals of the cultivation and management of the stands and their structure, respectively, aim to maximize tree growth and resistance to various stresses and disturbances, rather than optimizing their productivity (Hahn et al., 2021).

To reduce the risk of future windthrows in the spruce stands, it is recommended to improve young plantation composition by introducing 30-40% beech species (Govedar et al., 2018).

The efficiency of the establishment works of forest vegetation on the surface of the affected plots could be achieved if there were conditions for direct sowing, with certified seeds of spruce, fir, larch and beech species.

It is also necessary to analyze the post-disturbance time period and the intensity of the disturbance (Camarero et al., 2021), in order to evaluate the growth and development dynamics and respectively the resistance of future stands, in a spatio-temporal approach.

Currently, it is necessary to promote forestry policies and strategies that ensure the reduction of investment risks for forest owners, in order to promote stable forests, with a diversified structure, that provide multiple ecosystem services (Fuchs et al., 2024), under optimal conditions of administration and management.

The efficient implementation management of ecological restoration projects in the case of the forests affected by the devastating effect of climate change must be oriented towards both nature and the market. Consequently, ecological and economic objectives will be harmonized at a regional scale, in order to promote sustainable development in the region with high functional efficiency (Zhao et al., 2025).

CONCLUSIONS

The direction of the wind that caused the damage in the studied stands was from the NE exposure, which, according to the compartment descriptions in the forest management plan, accounts for 11% of their surface area.

In the context of global climate change, accurately determining the predisposing and triggering factors of windthrow and windbreak in spruce stands in the mountain zone is relatively difficult for various geographical areas.

The implementation of ecological rehabilitation works in spruce stands affected by extreme weather events presents a series of specific challenges related to the vegetation conditions and the morphological and ecological characteristics of these species.

Natural regeneration has been highly effective in 38.80% of the affected area, particularly in the upper part of the slopes, at distances of 300-400 meters from the unaffected spruce stands, which produced abundant seed during the period 2011-2014.

Although the Forest Code stipulates that the conservation and regeneration fund for forests should represent between 10-25% of the value of harvested wood, including main and accidental products I, for the ecological rehabilitation of the affected stands studied, this percentage is insufficient.

For optimal ecological rehabilitation of spruce stands that have been completely affected by various calamities, the conservation and regeneration fund must cover the cost of all necessary works, as established by the projects and execution estimates prepared for this purpose.

Given the current climate instability, the specific strategies for forest management of coniferous stands vulnerable to destabilizing factors must be integrated into adaptive forest management.

In extreme and exceptional situations, the conservation and regeneration fund for forests can be represented by the total value obtained from the sale of accidental products I, regardless of the owner or the administrator of the forest fund. This aspect must be urgently implemented in the Forest Code.

The consolidation of the ecosystem stability of spruce stands in the mountain zone, affected by various calamities, must be carried out as quickly as possible by introducing beech species through direct sowing under the canopy, and by expanding existing mixtures of spruce, fir, and beech species.

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