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CAUSES AND CONSEQUENCES OF LARGE-SCALE WINDTHROW ON THE DEVELOPMENT OF FIR-BEECH FORESTS IN THE DINARIC MOUNTAINS
VZROKI IN POSLEDICE VELIKOPOVRŠINSKEGA VETROLOMA NA RAZVOJ BUKOVO-JELOVIH GOZDOV V DINARSKEM GORSTVU

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ABSTRACT

We investigated several aspects of windthrow that are relevant to our understanding and management of forest ecosystems. As an example, we used an extreme event in December 2017, when the strongest storm in recent history occurred in the Slovenian Dinaric High Karst. We examined influential factors such as soil properties, wind speed, precipitation and ecological consequences for the affected forests. Soil properties were measured around standing and fallen silver fir trees at all three research sites. Tree species composition in the regeneration was observed on plots with chemical and acoustic ungulate deterrents and on control plots without deterrents. Economic estimates of yield loss due to damage were calculated at the national level. A model of the potential threat from windthrow was also developed based on data collected from windthrow events and meteorological data over the past 20 years. Our results indicate that soil depth and mineral fraction depth were similar at sites with and without damaged trees and were not the determining factors for tree toppling. Plots with acoustic deterrents showed the most effective regeneration development, the least decline in silver fir and the greatest increase in noble hardwood seedlings, while plots with chemical deterrents showed the least browsing damage. The estimated economic loss of €16.1 million is 6.6% less than the harvest under normal conditions. The economic loss was relatively low due to the nature of the storm, with the predominant type of damage being uprooted trees with no damaged trunks. The windthrow hazard model revealed that a large number of consecutive events with strong winds in each section weakened the stand, which was subsequently knocked down during the next extreme wind and rainfall event.

Key words: natural forest regeneration, windthrow, economic loss, browsing, ungulate deterrents, forest soil properties, potential threat model

IZVLEČEK

Raziskali in analizirali smo problematiko vetrolomov z različnih vidikov, pomembnih za naše razumevanje in upravljanje gozdnih ekosistemov. Kot primer smo uporabili ekstremni dogodek iz decembra 2017, ko je slovenski visoki dinarski kras prizadel najmočnejši vetrolom v novejši zgodovini. Da bi razumeli vzroke in ekološke posledice te obsežne motnje, smo gozdove na treh različnih lokacijah v Dinarskem območju preučevali iz različnih vidikov, ki so lahko vzroki za škodo zaradi vetroloma ali pa njegova posledica. Lastnosti tal smo izmerili okoli stoječih in podrtih dreves na vseh treh raziskovalnih lokacijah. Prav tako smo na vseh lokacijah spremljali sestavo drevesnega mladja na ploskvah, opremljenih s kemičnimi in zvočnimi odvračali za parkljarje, ter kontrolnih ploskvah brez odvračal. Ekonomske ocene zaradi izgube donosa zaradi škode smo izračunali za nacionalno raven. Na podlagi zbranih podatkov vetrolomov in meteoroloških podatkov v zadnjih 20 letih smo izdelali model potencialne ogroženosti zaradi vetrolomov. Lastnosti gozdnih tal niso vzrok za vetrolom, vendar pa spadajo med dejavnike vpliva na poškodbe dreves zaradi vetroloma. V naši raziskavi so se talne lastnosti na mestih s poškodovanimi drevesi in brez njih izkazale za statistično neznačilne in niso bile odločilen dejavnik za prevračanje dreves. Ploskve z zvočnimi odvračali so pokazale najuspešnejši razvoj mladja, tj. najmanjši upad pri jelki in največje povečanje pri plemenitih listavcih, medtem ko so ploskve s kemičnimi odvračali pokazale najmanjšo škodo zaradi objedanja. Ocenjena gospodarska izguba v višini 16,1 milijona evrov je za 6,6 % manjša od poseka v običajnih okoliščinah. Gospodarska škoda je bila zaradi narave neurja razmeroma majhna, saj je bila večina škode v obliki izruvanih dreves brez poškodovanih debel. Model nevarnosti pojava vetrolomov je pokazal, da je veliko število zaporednih dogodkov z močnimi vetrovi na vsakem odseku oslabilo sestoj, ki je bil posledično uničen ob naslednjem ekstremnem dogodku vetra in padavin.

Ključne besede: naravno mladje, vetrolom, gospodarska škoda, objedanje, odvračala za parkljarje, lastnosti gozdnih tal, modeliranje tveganja

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1 INTRODUCTION

1 UVOD

The risks associated with future forest management are increasing due to the increasing frequency of extreme weather events (Nagel et al., 2017). Storms, as the most widespread natural disaster, cause unprecedented damage and economic losses (Schelhaas et al., 2003; Gardiner et al., 2013). Several large-scale windthrow events, such as Kyrill (2007), Gudrun (2005), Lothar (1999), Vivian (1990) and Liebke (1990), have raised many questions and concerns about the environmental and economic consequences of such disturbances (collected in Wermelinger et al., 2017). In December 2017, a windthrow in Slovenia destroyed 2.2 million m^3 of trees, with peak wind speeds exceeding 200 km/h. The most affected tree species were Norway spruce (*Picea abies*; hereafter spruce), silver fir (*Abies alba*; hereafter fir) and common beech (*Fagus sylvatica*) (Krajnc and Breznikar, 2019).

The restoration of damaged forests is the most important goal after disturbance. While small-scale disturbances trigger advance regeneration of late successional species (Woods, 2004), large-scale disturbances usually destroy most of the tree canopy and create favourable conditions for pioneer tree species (Jaloviar et al., 2017). Artificial regeneration and restoration through planting are common in countries where clearcutting is allowed, but less so in those where natural regeneration with shade-tolerant species is used (Čater and Diaci, 2017). In temperate forests, succession following large-scale disturbance (e.g., windthrow or ice) usually includes an initial pioneer stage before a late successional community of shade-tolerant species forms (Korpel', 1995; Fischer and Fischer, 2012; Jaloviar et al., 2017). Close-to-nature forest management in Slovenia is mainly based on natural regeneration and the release of advance regeneration. Therefore, understanding the recovery of existing tree species after disturbance in mixed forests is crucial for their successful restoration (Čater and Diaci, 2017).

While some studies have documented that early successional stages and successional changes due to strong herbivore pressure (Faliński, 1998) are prolonged by abundant food after storms (Wohlgemuth et al., 1995), other studies provide no evidence that browsing ungulates threaten the natural regeneration of forest stands in windthrow areas (Senn et al., 2002; Senn and Suter, 2003). In particular, natural regeneration of silver fir is often suppressed by high ungulate populations (Heuze et al., 2005; Fischer et al., 2013).

Although the spatial and temporal occurrence of forest storms is highly stochastic (Shikhov et al., 2019), several studies have attempted to identify the key factors that influence the occurrence of such disturbances: soil properties (depth, soil characteristics), stand parameters (diameter, slenderness, structure of fallen trees) or even possible internal wood anomalies and defects (ring peeling, wet core) that increase the exposure and vulnerability of stands to wind disturbance.

To study the properties of fallen trees, most analyses consider two components of tree structure: the above-ground component of the trunk, branches and leaves exposed to wind, which can cause breakage under load, and the root system, which anchors the tree in the soil against the wind (Moore, 2014). Waterlogged soils are often related to the intensity of windthrow damage; waterlogging after heavy rains reduces soil strength (Smiley et al., 1998) and can lead to windthrow. The root system facing the wind remains intact, while the descending roots slip out of the weakened soil (Crook and Ennos, 1996). The susceptibility of trees to windthrow depends on tree size, tree age, root system, soil type, soil texture and wind speed (Cremer et al., 1982). In shallow soils, the root system is usually more susceptible, although some studies have reported that the depth of the root plate has no effect on tree anchorage or failure (Koizumi et al., 2007).To understand the impact of the large-scale windthrow of December 2017 on Slovenian forests, we set the following objectives:

- determine whether the physical soil properties of damaged (uprooted trees) and undamaged forest microsites differ,
- study the development of natural regeneration in damaged areas and evaluate the effectiveness of chemical and acoustic deterrents against ungulates,
- estimate economic losses due to windstorms,
- model the potential risk of windthrow in the future.

2 METHODS

2 METODE DELA

2.1 Research sites

2.1 Lokacije raziskav

The research sites were located in the Dinaric High Karst region, which extends southeast to the Balkan Peninsula (Gams, 1969) (Fig. 1). The forests mainly consist of uneven-aged silver fir-beech and spruce forest stands classified as the *Omphalodo-Fagetum* forest vegetation type (Marinček and Čarni, 2002). In all selected sites, the required salvage logging exceeded 30 m^3/ha after the extreme weather events in December 2017 (Table 1).

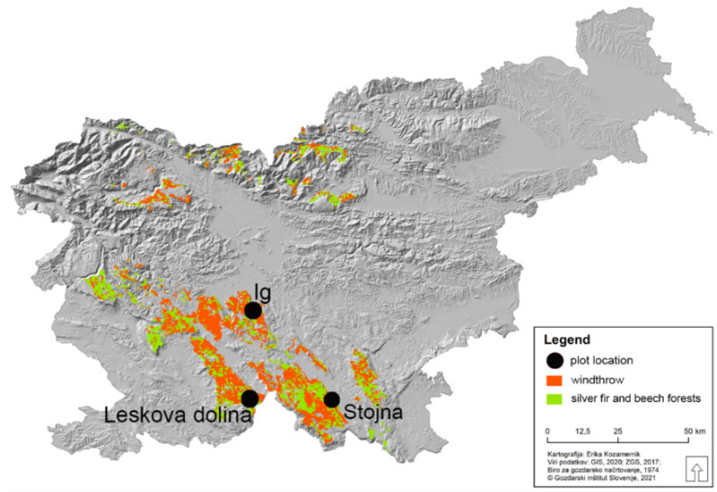

Fig. 1: Locations of the research sites with windthrow areas within silver fir-beech forests in Slovenia

Slika 1: Lokacije raziskav z območja vetrolomov znotraj jelovo-bukovih gozdov v Sloveniji

Table 1: Characteristics of the research sites. Average temperature and precipitation data were obtained for the period 1990–2020. Growing stock refers to the pre-disturbance conditions (Čater, 2021).

Preglednica 1: Značilnosti raziskovalnih lokacij. Podatki o povprečni temperaturi in padavinah so bili pridobljeni za obdobje 1990–2020. Lesna zaloga se nanaša na stanje pred motnjami (Čater, 2021).

Site	Latitude Deg (^{0}) N	Longitude Deg (^{0}) E	Mean annual air T (^{0}C)	Annual precipitation (mm)	Growing stock (m^3/ha)
Ig	45^0 55'	14^0 29'	8.5	1430	330
Leskova dolina	45^0 38'	14^0 28'	5.8	1650	532
Stojna	45^0 37'	14^0 50'	7.2	1526	380

2.2 Soil conditions and soil sampling
2.2 Talne razmere in vzorčenje tal

Soluble and permeable limestone and dolomite predominate throughout the study area. The soils are directly dependent on the parent material and consist of different Lithosols, Rendzinas, Cambisols and Luvisols (Vrščaj et al., 2017) that mosaic into each other. The terrain is rugged, with alternating depressions and hilly mountains. The physical and chemical soil properties are favourable, but the variable depth, the presence of surface rocks and the lack of water make this region mainly suitable for forests (Vrščaj et al., 2017).

Due to the different characteristics of tree root systems, our study focused only on soil conditions around silver fir trees. Soil depth, soil organic carbon (SOC), soil organic matter, nitrogen, C/N ratio, pH and texture were measured and sampled at all three sites (Fig. 1), in microsites with 30 randomly selected fir trees: 15 standing, undamaged trees and 15 wind-thrown trees. Soil depth measurements and soil samples were collected from the windward side of the selected trees, 2 m from the centre of the trees or the centre of the fallen trees, using a semi-circular conical T-probe. For each tree, 10 systematic measurements were taken. Values from the different soil depths were averaged and soil samples were pooled. During the sampling and measurement of soil depth, the organic and mineral parts of the soil were separated. Only samples from the mineral part were used for the chemical analyses. Also, only the depth of the mineral part was considered for the study.

Mineral soil samples were air-dried immediately after collection from the field. The samples were weighed and crushed after stones and roots were removed. An analiquot of the sample was analysed for the concentrations of SOC and total nitrogen (TN) in the soil by dry combustion using a CNS analyser (Elemental Analyzer LECO CNS 2000, St. Joseph, MI, USA). The volume of stones in the soil was evaluated, and the C to N ratio was calculated from their concentrations. Soil pH was determined in a 0.01 M $CaCl_2$ solution.

2.3 Natural regeneration and ungulate deterrents
2.3 Naravno pomlajevanje in odvračala za parkljarje

We selected sites in the regeneration phase with similar light conditions, slope and exposure, away from forest roads and other objects, and with clear signs of recent deer activity (fresh droppings, tracks or browsing marks). The selection criteria also included the presence of fir regeneration, the species with the greatest regeneration problems in Dinaric High Karst forests (Diaci et al., 2010). At each site, two plots with different types of ungulate deterrents (chemical and acoustic) and a control plot without any ungulate deterrents were established to assess browsing damage (Fig. 2). The plots were 30 x 30 m, and regeneration inventory was conducted on four 10 x 2 m strips within each plot. To avoid interactions, the minimum distance between plots was 50 m (Kuijper et al., 2014; van Ginkel et al., 2019). On the chemical plots, we placed four chemical deterrents with an operational range of 10 m. They consisted of a special foam (Hagopur scent fence foam) and Hagopur chemical spray, which mimic the odour of various ungulate predators (wolf, brown bear, European lynx) and humans (Hagopur, 2022). The mixture was refreshed every 2 months (the manufacturer guarantees its effectiveness even if it is refreshed twice a year). However, the effectiveness of this deterrent decreases with decreasing temperatures, or rather, it functions optimally above 10 °C. The other plots with deterrents were equipped with an acoustic deterrent with an operational range of 25 m. They were placed in the centre of the plot and regularly checked for proper functioning. They randomly generate different sounds every 15 minutes in the audible range and in the frequency band of the upper hearing limit of 15kHz. The deterrents were constructed in our laboratory for electronic devices and are charged by solar cells.

An inventory of the tree species regeneration was conducted at all study sites, first in October 2019 before the installation of the deterrent and for a second time in May 2021. It was conducted according to the methodology of the Slovenia Forest Service (Terglav et al., 2017). All tree species were identified by species/genus and classified into one of the following height classes according to browsing damage:

- Up to 15.0 cm (class 0),
- 15.1 to 30.0 cm (class I),
- 30.1 to 60.0 cm (class II),
- 60.1 to 100.0 cm (class III) and
- 100.1 to 150 cm (class IV).

When calculating browsing damage, we considered only height classes I–IV, according to previous studies in Slovenia (Terglav et al., 2017). However, in the additional part, where we represent tree species composition, we took into account all height classes. This also because fir mostly appeared only in height class 0.

2.4 Estimation of economic loss
2.4 Ocena gospodarske škode

Data on the quantitative felling of individual tree species were obtained from the Slovenia Forest Service's Timber database, and included the sanitary logging caused by the storm and carried out between December 2017 and the end of 2019. The analysis was performed for all regional units, although the damage in individual units was insignificant and mainly concentrated in the southern part of the country (Fig. 1). To estimate the total reduced cut, the theoretical assortment composition of *Omphalodo-Fagetum* (Appendix 1) was first determined according to Gorše (2009). The theoretical assortment structure based on actual felling was determined by multiplying the total amount of felling from the Timber database by the proportions of each quality assortment class (Gorše, 2009). For assortment losses due to wind storms, tables were used according to Žgajnar (1990), who describes quantitative losses due to timber bucking (Appendix 2). Field observations confirmed that the December 2017 storm damage was entirely in the form of uprooted trees, so windstorm damage ratios were used. The estimated losses represent the difference between theoretical and actual cut. The 2018 roundwood market prices in Slovenia monitored by the Slovenian Forestry Institute (WCM, 2021) were used to estimate the total economic damage.

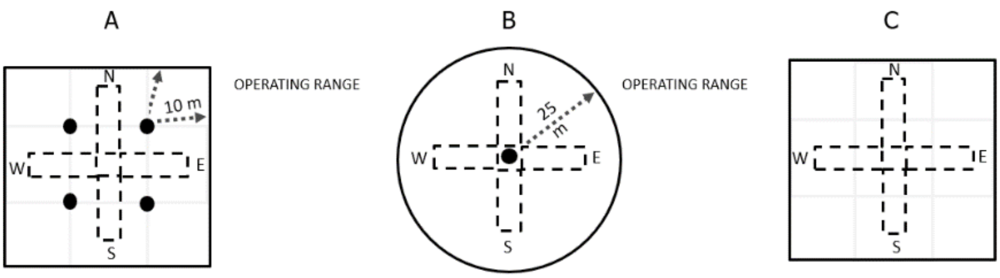

Fig. 2: Experimental design. A – plot with chemical deterrents, B – plot with acoustic deterrents, C – control plot. The dashed line shows the inventory plots, and the black dots mark the position of the deterrents.

Slika 2: Zasnova poskusa. A – ploskev s kemičnimi odvračali, B – ploskev z zvočnim odvračalom, C – kontrolna ploskev. Črtkane črte prikazujejo popisne ploskve, črne pike pa položaj odvračal.

2.5 Windthrow potential threat model
2.5 Model potencialne ogroženosti zaradi vetrolomov

We took into account the entire Slovenian forest area, which is divided into 29,837 sections (Slovenia Forest Service, 2019). For each section, we collected data on windthrow events in the last 20 years, where both fir and spruce occur. We provided an overview of windthrow events of fir and spruce in the sections in terms of the percentage of rocks and parent material for each section. Twenty years of meteorological data from 185 stations (Slovenian Environment Agency) were used, and each section was connected to the nearest meteorological station. Normal values for wind speed, wind direction and precipitation were determined for each section. Basic statistics on the occurrence of windthrow were performed. Based on the data on the occurrence of windthrows in the last 20 years in the forest sections and the meteorological data, a 20-year dataset of meteorological conditions and windthrow events for each section was established. Linear regression analysis was used to quantify the relationships between variables and to assess the potential threat to coniferous forests (fir and spruce) during high winds in Slovenia.

3 RESULTS
3 REZULTATI
3.1 Soil conditions
3.1 Talne razmere

Soil types near the selected fallen and standing silver fir trees were relatively homogeneous (Leskova dolina – Eutric Cambisols and Rendzinas, Stojna – Rendzinas and Lithosols, Ig – Eutric Cambisols and Rendzinas) (Vrščaj et al., 2017). Stojna soils were extremely shallow and contained almost no mineral soil horizon. Silver fir trees were able to grow on rocks, while their main roots reached deep soil pockets between the rocks. Therefore, soil depth measurements and soil sampling were not performed on eight out of thirty microplots, and physio-chemical analyses of soil mineral content were not performed on all plots. Even for shallow soils (Lithosols), the conditions on the microplots were homogeneous and comparable in terms of the location of fallen and standing trees, suggesting that both categories of trees were present on these shallow soils. A total of 22 mineral soil composite samples were collected at all three sites (Leskova dolina – 10 samples, Ig – 9 samples, and Stojna – 3 samples).

At all sites, the soils were predominantly shallow to moderately deep (organic and mineral horizons combined) and rocky. Soils at microsites with fallen trees averaged 23.3 cm deep, while at microsites with standing trees, they averaged 22.5 cm deep. No statistically significant differences were found between the mineral fraction depths. Also, no statistically significant differences were observed between the microsites with fallen and standing trees for any of the parameters studied (Table 2).

3.2 Natural regeneration and ungulate deterrents
3.2 Naravno pomlajevanje in odvračala za parkljarje

Natural regeneration of European beech (hereafter beech), fir, spruce and sycamore maple was pres-

Table 2: Physio-chemical soil parameters of the soil samples collected in the vicinity of fallen and standing silver fir trees. Only the mineral fraction of the soil was considered in the analysis (C_{org}: soil organic carbon (SOC), TN: total nitrogen, % sand, coarse silt, fine silt and clay as average soil texture).

Preglednica 2: Fizikalno-kemijski parametri tal odvzetih vzorcev tal v bližini podrtih in stoječih jelk. Pri analizi je bil upoštevan samo mineralni delež tal (C_{org}: organski ogljik v tleh (SOC), TN: skupni dušik, % peska, grobega melja, drobnega melja in gline kot povprečne teksture tal).

	Valid N Fallen	Valid N Standing	Mean Fallen	Mean Standing	t-value	Std. dev. Fallen	Std. dev. Standing	df	p
C_{org} (%)	11	11	5.594	5.292	0.375	2.129	1.616	20	0.711
TN (%)	11	11	0.314	0.296	0.377	0.122	0.099	20	0.710
pH	11	11	5.450	5.312	0.453	0.671	0.752	20	0.655
Sand (%)	11	11	2.245	3.282	-0.913	1.159	3.581	20	0.372
Coarse silt (%)	11	11	16.509	16.736	-0.176	3.073	2.998	20	0.862
Fine silt (%)	11	11	47.664	46.364	0.443	7.629	6.059	20	0.663
Clay (%)	11	11	33.582	33.618	-0.010	9.978	7.144	20	0.992
Soil depth total	176	162	23.278	22.463	0.373	21.490	18.452	336	0.710
Soil depth min.	176	162	11.159	11.438	-0.168	16.343	13.996	336	0.867

The results in Table 2 show soil depth and analyses of soil samples taken from the mineral part of the soil.

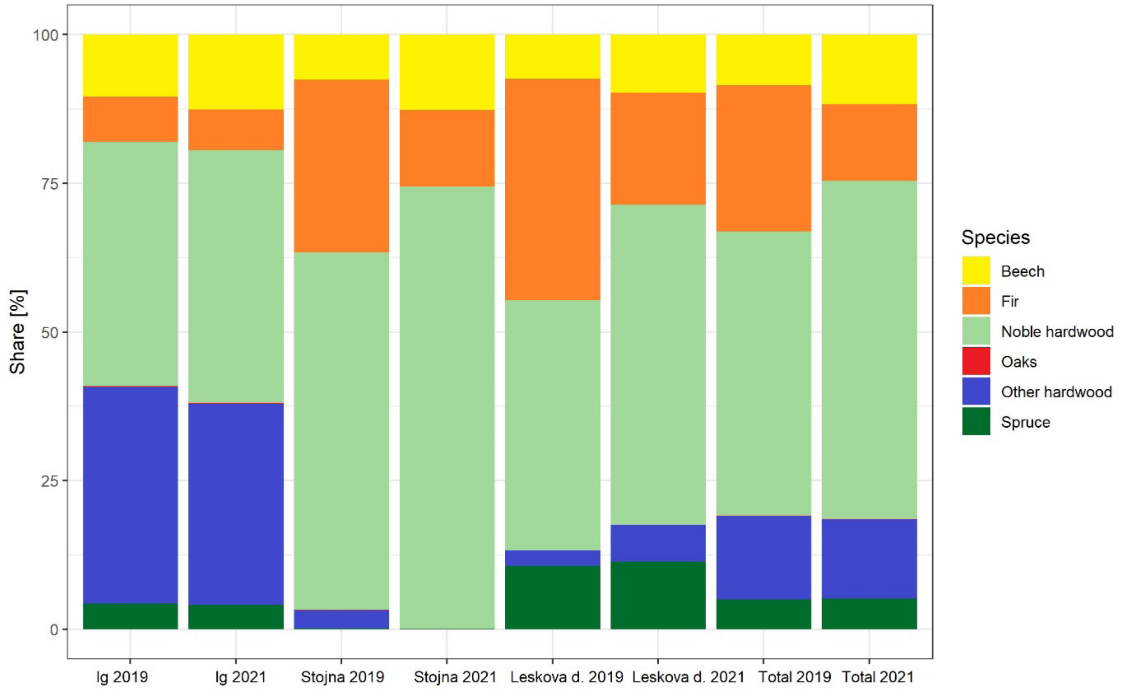

Fig. 3: Tree species composition at research plots in the 2019 and 2021 regeneration survey. Noble hardwoods = *Acer pseudoplatanus, A. platanoides, Tilia cordata, T. platyphyllos and Ulmus glabra*. Other hardwoods = *Sorbus aria, S. aucuparia, S. torminalis, Ilex aquifolium, Fraxinus ornus* and *Acer obtusatum*. Please note that the proportion of oaks is too small to be visible in the figure.

Slika 3: Sestava mladja drevesnih vrst v popisih, opravljenih leta 2019 in 2021 na opazovanih ploskvah. Noble hardwood (plemeniti listavci) = gorski javor, ostrolistni javor, lipa, lipovec, gorski brest; other hardwood (drugi trdi listavci) = jerebika, brek, mokovec, bodika, mali jesen, topokrpi javor. Delež hrastov v pomladku je prenizek, da bi bil viden na sliki.

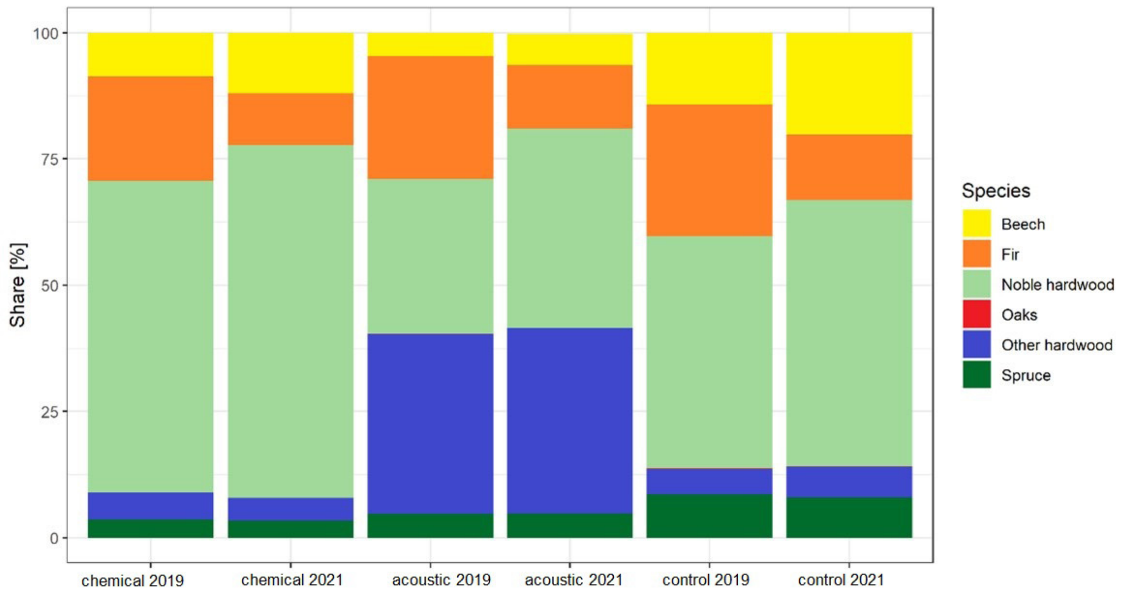

Fig. 4: Tree species composition in the 2019 and 2021 advance regeneration survey by different plot types (control, chemical deterrents, acoustic deterrents). Noble hardwoods = *Acer pseudoplatanus, A. platanoides, Tilia cordata, T. platyphyllos* and *Ulmus glabra*. Other hardwoods = *Sorbus aria, S. aucuparia, S. torminalis, Ilex aquifolium, Fraxinus ornus* and *Acer obtusatum*. Please note that the proportion of oaks is too small to be visible on the figure.

Slika 4: Sestava mladja glede na različne tipe ploskev (kontrolne ploskve, ploskve s kemičnimi odvračali, ploskve z zvočnimi odvračali) in leto popisa. Noble hardwood (plemeniti listavci) = gorski javor, ostrolistni javor, lipa, lipovec, gorski brest; other hardwood (drugi trdi listavci) = jerebika, brek, mokovec, bodika, mali jesen, topokrpi javor. Delež hrastov v pomladku je prenizek, da bi bil viden na sliki.

Table 3: Browsing damage in 2019 and 2021 expressed as the average of height classes I to IV for each species: (a) comparison between sites and (b) comparison between different plot types. Np = not present.

Preglednica 3: Škoda po objedanju v letih 2019 in 2021, izražena kot povprečje višinskih razredov (od I do IV) drevesnega mladja za vsako vrsto; (a) primerjava med lokacijami in (b) primerjava med različnimi tipi ploskev. Np = vrsta ni prisotna.

a)	2019			2021		
	Ig	Leskova d.	Stojna	Ig	Leskova d.	Stojna
Spruce [%]	42.1	6.0	np	74.4	31.0	np
Beech [%]	54.2	8.0	23.6	52.5	45.0	26.0
Fir [%]	np	14.3	np	np	np	np
Oaks [%]	np	np	np	np	np	np
Other hardwoods [%]	76.0	46.3	100.0	89	71.0	np
Noble hardwoods [%]	88.6	76.6	83.7	100.0	91.0	99.0
Conifers [%]	41.4	7.0	np	73.0	31.0	np
Deciduous [%]	75.3	63.5	66.1	85.0	83.0	73.0
Total [%]	72.9	58.2	65.5	84.0	78.0	73.0
b)	**2019**			**2021**		
	chemical	acoustic	control	chemical	acoustic	control
Spruce [%]	np	np	25.0	np	np	np
Beech [%]	21.7	24.4	27.3	39.1	13.5	68.4
Fir [%]	35.8	13.5	30.0	32.4	46.3	41.4
Oaks [%]	np	np	np	np	np	np
Other hardwoods [%]	79.1	81.2	80.2	89.7	95.2	88.2
Noble hardwoods [%]	85.9	74.5	59.5	83.3	87.8	69.0
Conifers [%]	20.0	22.7	27.1	39.1	15.4	68.4
Hardwoods [%]	72.7	72.1	57.6	79.6	87.0	68.6
Total [%]	70	69	53	78	83	69

ent at all three survey sites. At the first survey in 2019, the proportion of fir was lowest at the Ig site, but the proportion of other hardwood species was high. At the Stojna site, there was almost no spruce and a high proportion of noble hardwood species. Significant changes were observed after the second survey (2021) in Leskova dolina and Stojna in the form of a decreasing proportion of fir and a higher proportion of hardwood species. At all sites in total, the proportion of beech increased by 50% between the two surveys (Fig. 3).

An increase in noble hardwood species and beech and a decrease in the proportion of fir were observed on all plots. The greatest changes were observed on plots with chemical deterrents. On plots with acoustic deterrents, the decrease in fir was lowest and the increase in noble hardwoods was highest (Fig. 4).

In 2021, browsing damage increased at all sites compared to 2019: up to 11% in Ig, 20% in Leskova dolina and 7% in Stojna (Table 3a). At Ig, we observed the highest browsing damage in both years of the inventory. From the lowest to the highest browsing damage by species or species groups in 2019, the results were as follows: Spruce – Beech – Other hardwoods – Noble hardwoods. In 2021, the situation was the same, with the exception of spruce, which was browsed more intensively than beech. Fir was represented only in Leskova dolina in height classes I–IV, which explains the browsing damage of 0.0. Among the different plot types, browsing damage increased most on the control plots and least in the plots with chemical deterrents (Table 3b).

3.3 Estimation of economic loss

3.3 Ocena gospodarske škode

The December 2017 windstorm resulted in the highest amount of sanitary logging due to wind damage since 1995 (Fig. 5a). In 2018, storm-related logging accounted for 46% of total state-wide logging. This percentage remained high in 2019 at 17%. Spruce accounted for the majority of the logging (64%), followed by fir (24%) and beech (7%), while other tree species accounted for only 6% (Fig. 5b).

The total reduced cut was estimated at 205,855 m^3 (Fig. 6), with the highest reduced cut calculated for spruce (154,688 m^3), followed by fir (32,337 m^3) and beech (18,830 m^3) (Fig. 6). The largest total losses

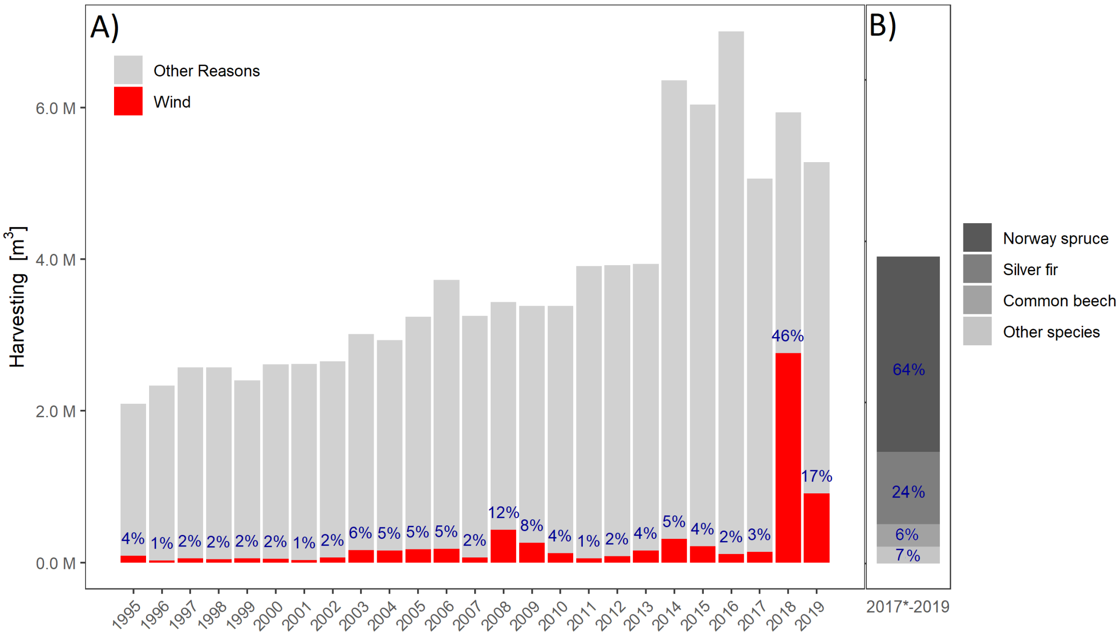

Fig. 5: a) The total volume of felled trees due to windstorms and other causes in Slovenia in the period 1995–2019 (Slovenia Forest Service, 2019). b) The proportion of tree species felled due to storms in the period December 2017 – December 2019.

Slika 5: a) Skupen volumen podrtih dreves zaradi vetra in drugih vzrokov v Sloveniji v obdobju 1995–2019 (Zavod za gozdove Slovenije, 2019). b) Delež poseka po drevesnih vrstah zaradi vetra v obdobju december 2017 – december 2019.

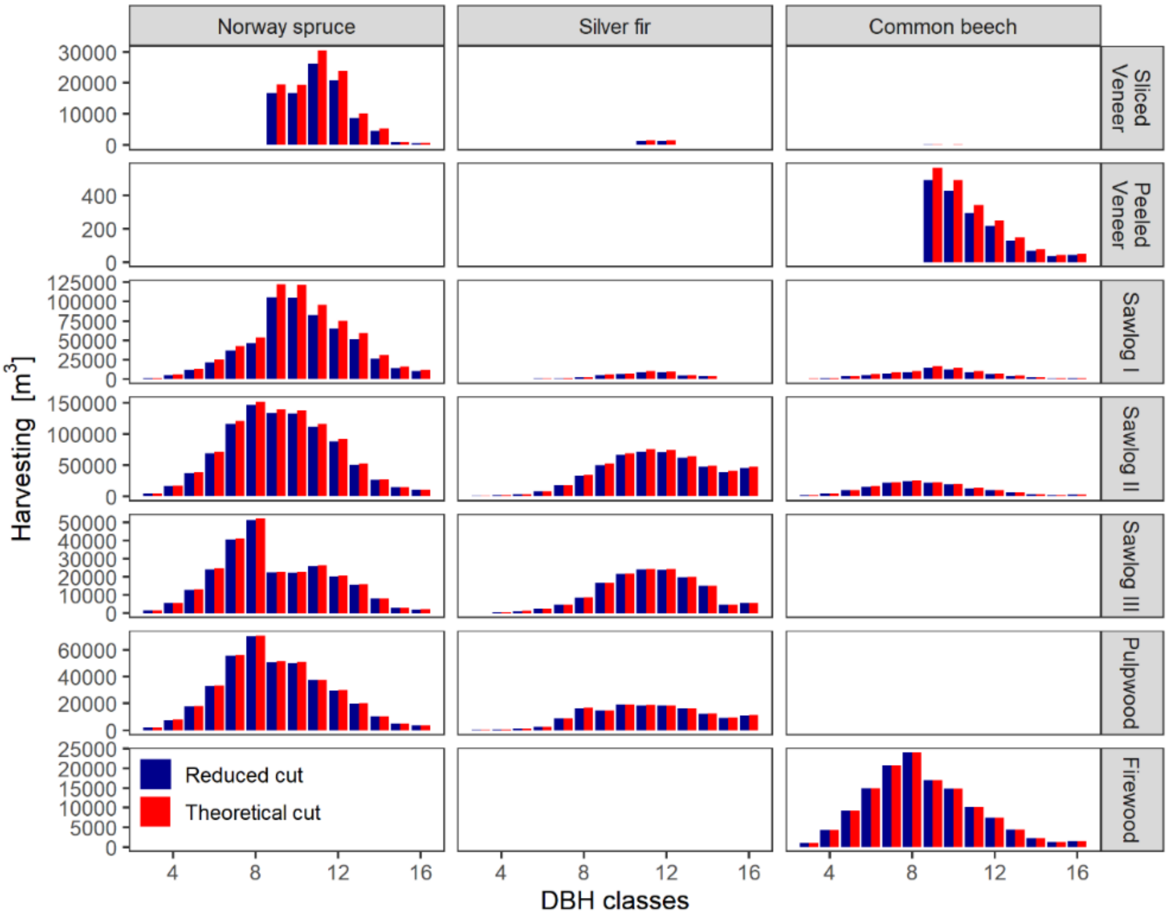

Fig. 6: The theoretical and actual reduced cut for the predominant tree species and different assortment classes

Slika 6: Teoretični in dejanski zmanjšani posek za prevladujoče drevesne vrste, ločeno po sortimentih were estimated for sawlogs I and sawlogs II. Conversion of the estimated assortments amounted to a total economic loss of €16.1 million, which is 6.6 % less compared to normal circumstances.

3.4 Windthrow potential threat model
3.4 Model potencialne ogroženosti zaradi vetrolomov

Windthrow was recorded in 46.3% of compartments between 1995 and 2017 and in 49.8% of compartments between 1995 and 2018. The last two extreme windthrow events (2017 and 2018) increased the proportion of damaged compartments by 3.5%.

Thirty-five per cent of events between 1995 and 2019, including spruce and fir stands in 29,062 compartments, occurred at sites with limestone bedrock. Analysis of windthrow events during the same period and in the same compartments shows that 45% and 60% of events occurred in compartments with 0–5% stoniness and rockiness, respectively.

With the available datasets for the last 23 years regarding windthrow, we tried to assess the dependence of days with precipitation above 30 mm and the number of days with strong winds above 6bf (>50 km/h) on the m^3 of fir that was windthrown. The main problem was the time discrepancy between recorded windthrow events in certain compartments and meteorological events (heavy rain, strong wind). SFS staff record windthrow events on an annual basis, and it is not necessarily the case that the event was recorded in the same year in which it occurred. This is evident for the last major windthrow event in December 2017. Several compartments were checked in January 2018, and the number of m^3 were recorded for that year and month. This is also the part of the variability seen in the data, as we were not always able to match certain m^3 with previous weather events correctly.

Fig. 7 shows the dependence between the number of days with precipitation above 30 mm and the number of days with strong winds above 6bf (> 50km/h) on the m^3 of fir that was windthrown in the selected area. Our results indicate that a large number of consecutive strong wind events in each compartment weakens the stand, which is knocked down during the next extreme wind and precipitation event.

4 DISCUSSION
4 RAZPRAVA

Windthrow risk depends on the interaction of numerous factors related to climate, wind speed and direction, topography, soil conditions, root shape and condition, tree and stand characteristics, and silvicultural treatments (logging, thinning, etc.) (Ruel, 1995).

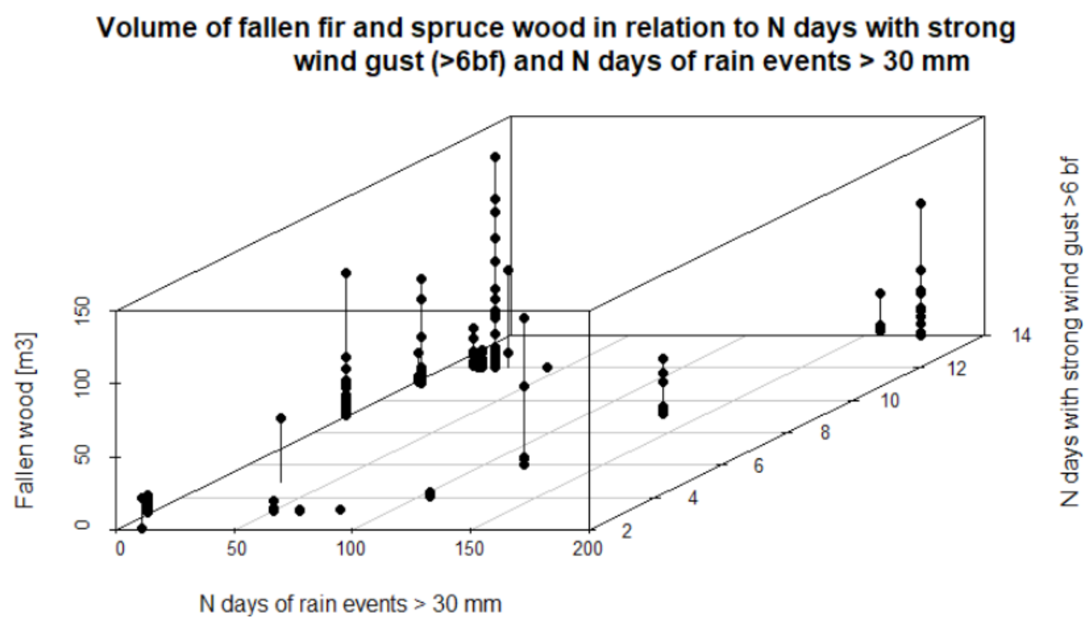

Fig. 7: Ratio between windthrown fir (m^3), number of days with strong winds and number of days with strong precipitation (rain events significant at 0.02586 *, strong winds significant at 0.03504 *). Equation: N[m^3] = 2.23 + 0.049*N_day[mm>30] + 0.913*N_days[bf>6]

Slika 7: Razmerje med količino lesa podrtih jelk (m^3), številom dni z močnim vetrom in številom dni z močnimi padavinami (nalivi značilno pri 0,02586 *, močni vetrovi značilni pri 0,03504 *). Enačba: N[m^3] = 2,23 + 0,049*N_dan[mm>30] + 0,913*N_dni[bf>6]

Soil condition is an influential factor in windthrow occurrence and can have a decisive influence on the extent of damage. Windthrow is often observed in stands growing on shallow or poorly drained soils (Dobbertin, 2002). Trees of the same mass have been found to be better anchored on deeper soils (Nicoll et al., 2008), whereas others report that trees on sites with deeper soils are more susceptible to windthrow due to the effects of soil fertility on tree growth, competition between trees and mutual protection of acclimated growth (Rebertus et al., 1997; Nowacki and Kramer, 1998; Mitchell, 2011).

At our study sites, strong wind gusts uprooted most mature silver fir (hereafter fir) trees, and only a few withstood the storm. We wondered why some older fir trees remained standing in windthrow areas. Our goal was to determine whether soil was the critical factor that allowed selected trees to withstand the wind. Soil shear resistance varies with soil texture and moisture content (Busby, 1965; Coutts, 1983) and decreases from sandy to loamy soils and with increasing moisture content (Busby, 1965). Hintikka (1972) confirmed that the force required to topple a spruce is twice as high on sandy soils as on clay soils. Higher soil moisture is caused by a higher proportion of clay and organic matter in the mineral portion. Coutts (1983) reported that roots in clay soils tend to pull rather than break; in saturated, fine-textured soils, sliding becomes the main reinforcing factor provided by roots. We were unable to confirm that the clay content of the soil was significantly higher in the vicinity of the fallen trees, but according to Moore (2014), heavy rainfall with accompanying strong winds can significantly reduce adequate support for roots. Studies at European sites indicate that fir is more resistant to high winds than spruce on well-drained soils because it can develop a deeper root system. In contrast, spruce is more resistant on moist soils, where its root system provides better anchorage (Polge, 1960).

Our results show that the soils at the two microsites with fallen and standing trees were predominantly shallow and did not differ significantly; shallow and deep soil pockets alternated over a small spatial distance, and root systems formed according to the geomorphological conditions of the terrain (Vrščaj et al., 2017). In the present study, soils were not found to be a determining factor for tree resistance to windthrow. The reasons for the resistance of adult fir trees could be root characteristics, root health, previous silvicultural treatment, tree slenderness, stand density and structure, crown length or a combination of all these factors. We recognize that the number of soil samples in the research is too small to draw definitive conclusions regarding the influence of the soil on the stability of trees, especially since it is an extremely variable karst soil, where the soil depth varies on a very small scale – from deep soil pockets to extremely shallow soil.

Once a windthrow affects a forest stand, we are interested in the damage caused from an economic perspective, but the estimation of economic losses can be a difficult task. Economic losses associated with windstorms are significant in European forests and vary by forest stand age and site index (Donis et al., 2020). In our case, the estimated total economic losses of €16.1 million or 6.6% less compared to regular logging under normal circumstances were not as drastic due to the nature of the damage, which was mainly uprooted trees. In the case of windstorms, the losses are much higher (Putz et al., 1983). However, in addition to the direct economic losses associated with timber cross-cutting, many side effects that contribute to long-term economic losses should also be considered, such as yield loss, damage to remaining trees and additional investment in regeneration (Nieuwenhuis and O'connor, 2001; Gardiner et al., 2013).

Typically, windthrows affect large areas at various phases of forest stand development, after which the damaged forests enter the regeneration phase. In systems based on natural regeneration, herbivory slows natural regeneration, reduces its quality and consequently alters the target tree species composition. Natural disturbances likely increase ungulate populations by increasing food supply.

In the immediate opening of tree canopies after disturbance and subsequent harvesting operations, it is crucial to select and favour site-adapted tree species; the survival of trees with advance regeneration is closely related to species plasticity, microclimate, species richness and herbivore density. Following disturbance, deciduous species may have an advantage over conifers because of the annual development of assimilation organs. The longevity of fir and spruce needles is difficult to compare with that of the foliage of beech and sycamore maple, which changes each year. Both fir and beech are shade tolerant and are the main co-existing tree species in the Dinaric Karst region. Fir is more sensitive to water deficits (Rolland et al., 1999); its photosynthetic activity is not limited to the growing season (Brinar, 1964) and reflects its greater shade tolerance by a lower pigmentation rate and thicker cuticle (Aerts, 1995).

The increase in beech observed in all our research plots is consistent with reports from other European countries on disturbed and undisturbed old-growth forests (Průša, 1985; Firm et al., 2009; Šamonil et al., 2013), where increased competition from beech is associated with fir decline, browsing and climate (Vrška et al., 2009; Diaci et al., 2011; Janík et al., 2014).

The reduction of fir saplings was consistent with the study of Čater (2021). However, the severity of the storm was not as intense as the 2014 ice storm (Čater, 2021), but a similar pattern was observed with both extreme-events. The observed reduction in the number of saplings should not be attributed only to the disturbance event but also to the natural reduction of sapling density over time and to browsing (Terglav et al., 2017), as observed on plots with acoustic deterrents.

Fir is among the most favoured species for browsing (Häsler and Senn, 2012); it recovers slowly from injury and exhibits delayed height growth when young, which can be a major drawback for its successful regeneration (Bee et al., 2009; Tanentzap et al., 2011). Sycamore maple has a better recovery capacity and faster growth, as confirmed in our study, whereas beech, with its high ecological plasticity and competitive ability, is less susceptible to browsing (Gill, 1992). Selective browsing behaviour with increased ungulate density probably has a negative effect on fir, a key species in Dinaric fir-beech forests, and a positive effect on the other two coexisting species, beech and spruce (Heuze et al., 2005; Klopčič et al., 2010). Compromised regeneration due to browsing can be prevented in several ways, but their effectiveness varies widely (Gilsdorf et al., 2002). According to our results, browsing cannot be prevented, but its effects can be mitigated. In our study, advance regeneration on plots with chemical deterrents suffered the least browsing damage, while regeneration on plots with acoustic deterrents developed most in line with forest management plans, with the smallest decline in the number of fir saplings and the greatest increase in noble hardwood species. Compared to other protective measures, such as fencing, deterrents were undoubtedly effective in several ways. We believe that further studies should emphasize their effectiveness and contribute to better recovery after disturbance.

Analyses of past windthrow events have shown that the December 2017 event was extreme and the most extensive in the last 30 years. It is important to note that both drastic and extreme events are unsuitable for analysis as they represent outliers in the numerical data and can distort the normal picture. Furthermore, more than 35% of the windthrow events occurred in fir and spruce trees on limestone bedrock. We should emphasise that most Slovenian fir and spruce stands grow on limestone bedrock, and therefore the data is biased by the distribution of stands according to the parent rock material. Specifically, 45% and 60% of the events occurred in areas with 0–5% stoniness and rockiness, respectively, suggesting that stoniness and rockiness mitigate the forces acting on trees during strong winds.

Our results are consistent with those of Klaus et al. (2011), who reported that the severity of windthrow was primarily due to a high proportion of conifers, complex orography and poor soil quality. A multiple regression model was applied to show the dependence between the damaged fir and spruce trees (expressed in m^3), the number of days with strong winds (maximum wind gust over 50 km/h) and the number of days with heavy precipitation (more than 30 mm per day). A large number of consecutive events with strong wind gusts and a large amount of precipitation weaken the stability of a stand, making it more susceptible to the next extreme wind and precipitation event. By counting extreme wind gusts and days when more than 30 mm of precipitation fall, a warning for windthrow events for each compartment can be created.

We believe that there are significant differences in the light environment and species adaptation between regular management, in which the canopy is gradually removed as part of a close-to nature silvicultural system, and disturbances that lead to rapid and abrupt changes in microclimate (Kermavnar et al., 2020). Our results confirm that wind disturbances accelerate the loss of fir due to lack of recruitment (Jaloviar et al., 2017) and promote the increasing dominance of deciduous tree species.

5 SUMMARY

Over the past decade, disturbances such as windthrow have greatly altered the appearance and functioning of our forests. Windthrow events cause economic damage and changes in forest ecosystems. They are hard to predict and have always been a constant in our forests. It is impossible to completely prevent damage from such strong and hurricane-force winds, but we could mitigate them through adaptive management. Proper information on location and damage would be the first step towards such a goal, to evaluate the extent, suggest a more appropriate management approach and also predict the locations of subsequent similar events in the future. After large-scale disturbances, younger forest development stages are particularly exposed to extensive browsing damage.

To understand the causes and ecological and economic consequences of windthrow, we studied the extreme event of December 2017, when the strongest storm in recent history occurred in the Slovenian Dinaric High Karst. At three research locations, we determined the soil properties, and on selected plots (plots with chemical and acoustic deterrents for ungulates and control plots without deterrents), we studied regeneration composition and browsing damage. Economic estimates of area loss due to damage were calculated at the national level. Based on collected data on windthrows and meteorological data from the last 20 years, we also developed a model of the potential threat posed by windthrow.

The research was carried out in the Dinaric High Karst region of fir-beech forests (*Omphalodo-Fagetum* association) at the Ig, Leskova dolina and Stojna sites. The parent material in the study areas consists mainly of limestone and dolomite, and the soil types are mosaically interwoven: mainly Leptosols, Rendzinas, Cambisols and Luvisols. Our goal was to determine whether the cause of the windthrow damage was associated with the soil conditions. Results from measurements and soil samples showed that soil parameters (depth, amount of organic carbon, amount of organic matter, pH, C/N ratio, and texture) were not statistically significantly different between 15 uprooted and 15 standing fir trees.

At all three research locations, the amount of natural regeneration and the ungulate browsing damage were examined, and the research plots were divided into control plots without ungulate deterrents and plots with chemical and acoustic deterrents. Within these 30 x 30 m plots on 2 x 10 m strips, we evaluated (counted) the regeneration and classified it into five height classes. We also determined whether the trees were browsed. The proportion of beech regeneration increased by at least 50% on all plots, as did the proportion of noble hardwoods, while the proportion of fir decreased during this period. The greatest changes were observed on the plots with chemical deterrents. On the plots with acoustic deterrents, the decrease in fir was smallest, and the increase in noble deciduous trees was most pronounced. We confirm that browsing intensity increased from 2019 to 2021, mostly on control plots and least on plots with chemical deterrents.

For the economic damage assessment, we used the database of the Slovenian Forest Service on quantitative felling of individual tree species, including post-disturbance restoration felling between December 2017 and the end of 2019. The total felling was estimated at 205,855 m^3, with the largest amount of felling calculated for spruce (154,688 m^3), followed by fir (32,337 m^3) and beech (18,830 m^3). The highest total losses due to windthrow were estimated for Roundwood I and Roundwood II grades. The conversion of the assessed assortments resulted in a total economic loss of €16.1 million, which is 6.6% less than the losses under normal conditions.

To create a windthrow risk model for Slovenian coniferous forests, we evaluated the entire area of Slovenia, which is divided into 29,837 compartments, using data from the Slovenia Forest Service from 2018. For each compartment containing fir and spruce, we selected data on windthrow events from the last 20 years. We also used measurements from 185 meteorological stations from the last 20 years and compared the data. We created a 20-year dataset of meteorological data and windthrow events for each compartment. Windthrow events were recorded in 46.3% of the compartments between 1995 and 2017 and in 49.8% of compartments between 1995 and 2018. We confirmed the dependence between the number of days with precipitation above 30 mm, the number of days with strong winds (>6bf) and the m^3 of fallen fir in each forest compartment. Our results confirm that windthrow accelerates the loss of fir due to lack of recruitment and promotes the increasing dominance of deciduous tree species.

6 POVZETEK

Ujme, med drugim tudi vetrolomi, v zadnjem desetletju močno krojijo podobo in delovanje naših gozdov. Vetrolomi povzročajo gospodarsko škodo in spremembe v gozdnih ekosistemih. Težko jih je napovedovati, vendar so stalnica v naših gozdovih že od nekdaj. Škode, ki nastanejo zaradi močnih in orkanskih vetrov ne moremo preprečiti, lahko pa jo omilimo z ustrezno prilagojenim gospodarjenjem. Za izvedbo ustreznih ukrepov, načrtovanje gospodarjenja ter predvidevanje verjetnih lokacij podobnih dogodkov v prihodnje potrebujemo informacijo o natančnem mestu in obsegu škode, ki so jo povzročili vetrolomi. Po velikopovršinskih motnjah so predvsem mlajše razvojne faze izpostavljene poškodbam zaradi objedanja rastlinojedih parkljarjev. Za boljše razumevanje vzrokov in ekoloških ter ekonomskih posledic vetroloma smo preučili ekstremni dogodek iz decembra 2017, ko je slovenski visoki dinarski kras prizadel najmočnejši vetrolom v novejši zgodovini. Na treh lokacijah smo preučevali lastnosti tal in sestavo naravnega mladja na ploskvah, opremljenih s kemičnimi in zvočnimi odvračali za odvračanje parkljarjev, in jih primerjali s stanjem kontrolnih ploskev brez odvračal. Ekonomske ocene zaradi škode smo ocenili za nacionalno raven. Na podlagi zbranih podatkov o vetrolomih in meteoroloških podatkov zadnjih 20 let smo oblikovali tudi model potencialne ogroženosti gozdov.

Raziskave smo opravili v jelovo bukovih gozdovih visokega dinarskega krasa (združba *Omphalodo-Fage-*

tum) na območju Iga, Leskove doline in Stojne. Matično podlago na območjih sestavljajo predvsem apnenci in dolomit, tipi tal se mozaično prepletajo: prevladujejo rendzine, rjava pokarbonatna tla in izprana rjava tla. Vzrok za veliko škodo, predvsem izruvanih jelk, smo iskali v talnih razmerah, vendar smo s pomočjo meritev in odvzema vzorcev tal ugotovili, da talni parametri (globina, količina organskega ogljika, količina organske snovi, pH, C/N razmerje ter tekstura okoli 15 podrtih in 15 stoječih jelk) niso statistično različni.

Uspevanje in številčnost naravnega mladja ter učinkovitost odvračal smo ugotavljali na vseh treh lokacijah, kjer smo oblikovali 30 x 30 m velike raziskovalne ploskve z zvočnimi in kemičnimi odvračali ter njihovo stanje primerjali s kontrolnimi ploskvami v dveh popisih leta 2019 in 2021 znotraj petih višinskih razredov. Naravno mladje glavnih drevesnih vrst se pojavlja na vseh raziskovalnih lokacijah. Delež bukovega mladja se je na vseh ploskvah povečal za najmanj 50 %, podobno tudi delež plemenitih listavcev, medtem ko se je delež jelke v istem obdobju zmanjšal. Največje spremembe smo potrdili na ploskvah s kemičnimi odvračali. Na ploskvah z zvočnimi odvračali je bil upad številčnosti jelke najmanjši, povečanje plemenitih listavcev pa najbolj opazno. Potrdili smo, da se je objedanje mladja povečalo v obdobju med letoma 2019 in 2021. Med različnimi vrstami ploskev se je škoda zaradi objedanja najbolj povečala na kontrolnih ploskvah in najmanj na ploskvah s kemičnimi odvračali.

Oceno gospodarske škode smo napravili s pomočjo podatkovne baze količine- poseka posameznih drevesnih vrst, vključno s podatki sanitarne sečnje po neurju med decembrom 2017 in koncem 2019 Zavoda za gozdove Slovenije. Ocenjeni skupni posek je znašal 205.855 m^3, največji za smreko (154.688 m^3), ki ji sledita jelka (32.337 m^3) in bukev (18.830 m^3). Največje skupne izgube zaradi vetroloma smo ocenili za hlodovino I in hlodovino II. S pretvorbo ocenjenih sortimentov ocenjujemo, da je nastala skupna gospodarska izguba v višini 16,1 milijona evrov, kar je za 6,6 % manj od običajnih razmer.

Za izdelavo modela ogroženosti iglastih gozdov zaradi vetrolomov smo upoštevali območje celotne Slovenije, ki smo jo razdelili na 29.837 sekcij ter uporabili podatke Zavoda za gozdove Slovenije iz leta 2018. Za vsak odsek, kjer se pojavljata jelka in smreka, smo izbrali podatke o vetrolomih za zadnjih 20 let. Uporabili smo tudi meritve 185 meteoroloških postaj za zadnjih 20 let ter podatke povezali. Izdelali smo 20-letni podatkovni niz meteoroloških podatkov in vetrolomnih dogodkov za vsak izbrani odsek. Vetrolome so med letoma 1995 in 2017 zabeležili na 46,3 % odsekov in 49,8 % med letoma 1995 in 2018. Potrdili smo odvisnost števila dni s padavinami nad 30 mm in števila dni z močnim vetrom (> 6bf) od m^3 podrtih jelk na posameznem odseku. Model nevarnosti pojava vetrolomov je pokazal, da je veliko število zaporednih dogodkov z močnimi vetrovi na vsakem odseku oslabilo sestoj, ki je bil posledično uničen ob naslednjem ekstremnem dogodku vetra in padavin.

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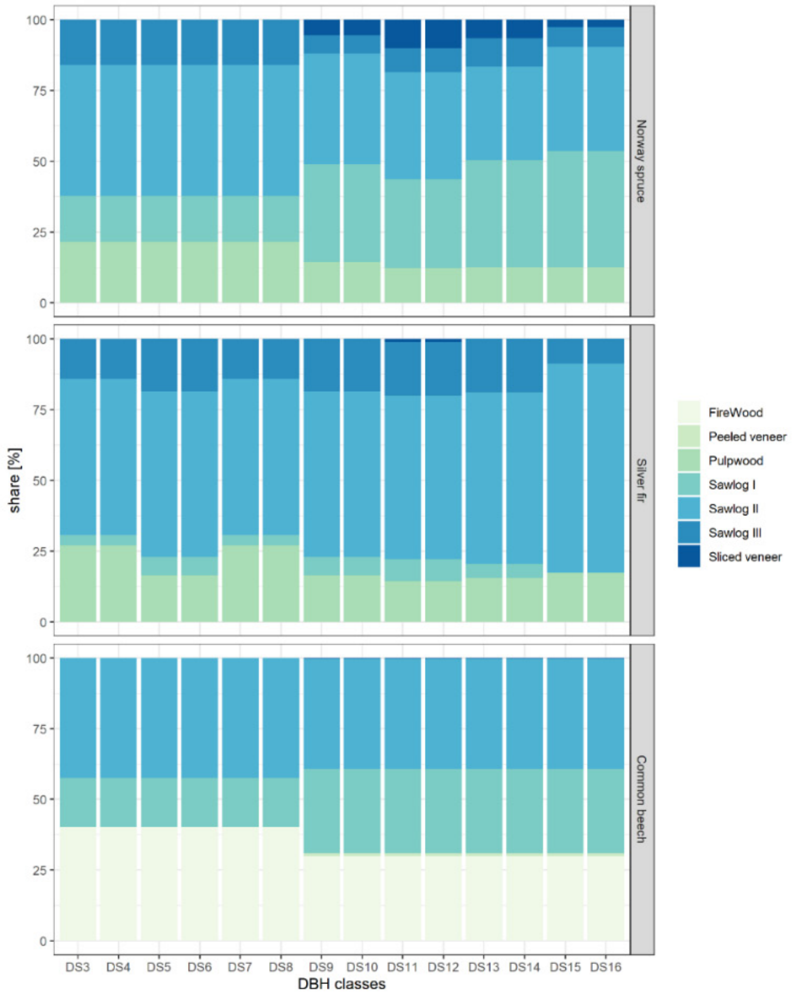
SUPPLEMENTARY MATERIAL

Appendix 1: Theoretical assortment structure of *Omphalodo-Fagetum* forest stands (Gorše, 2009)

Priloga 1: Teoretična sortimentna struktura gozdnih sestojev združbe *Omphalodo-Fagetum* (Gorše, 2009)



Appendix 2: Assortment losses due to wind damage (Žgajnar, 1990)

Priloga 2: Izgube sortimentov zaradi vetroloma (Žgajnar, 1990)

Damage type	Sliced veneer	Peeled veneer	Sawlog I	Sawlog II	Sawlog III	Pulpwood	Firewood
Uprooted trees	0.136	0.136	0.136	0.040	0.017	0.010	0.000
Windsnap (tree height > 2 m)	0.275	0.275	0.275	0.092	0.001	0.495	0.000
Windsnap (tree height < 2 m)	0.124	0.124	0.124	0.108	0.001	0.016	0.000

Appendix 3: Average prices of roundwood in EUR/m^3 for Norway spruce, silver fir, beech in autumn 2018 in Slovenia (WCM, 2021)

Priloga 3: Povprečne cene okroglega lesa v EUR/m^3 za smreko, jelko in bukev jeseni 2018 v Sloveniji (WCM, 2021)

Timber quality assortments	Common beech	Norway spruce	Silver fir
Sliced veneer	95	100	81
Peeled veneer	88	100	81
Sawlog I	80	85	75
Sawlog II	70	75	64
Sawlog III	55	50	48
Pulpwood	55	30	30
Firewood	58	45	45