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Investigation of the Effect of Topography and Stand Structure on Windthrow Damages: A Case Study from Düzce, Türkiye

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Abstract

Aim of study: The aim of the study was to determined the tree volume and damage level in windthrow areas and to assess the impact of topographic factors and forest structure on windthrow damaged.

Area of study: Our study was conducted within the Düzce Forest Management Directorate.

Material and methods: The windthrow areas within the boundaries of Düzce Forest Management Directorate were obtained from extraordinary yield reports. According to windthrow data verified using Google Earth, the borders for each damage were determined and transferred to ArcMap. The relationships between windthrow areas and enviromental parameters were determined using digital maps and forest management plans. Correlation analysis was applied to find out the relationship between windthrow areas and topographic and forest characteristics. Additionally, variance analysis was performed to determine if there were differences in terms of dominant aspects and forest types between windthrow areas and amounts. T-tests were conducted to determine if there were differences between windthrow areas and amounts and the dominant wind direction. Based on the statistically significant results, an intersect analysis was applied to environmental parameters to generate a windthrow susceptibility map.

Main results: Windthrow occurred mostly in the southwest aspect, in the Fir-Beech species and in the cd age classes. A statistically significant relationship ($p<0.05$) was found between windthrow area and tree diameter and elevation, and also between windthrow amount and elevation and site index. Moreover, significant relationships ($p<0.05$) were found in dominant aspect groups and species mix classes in with windthrow area.

Research highlights: Windthrow damage is a dynamic process, and it is important to determine its relationships with topographic and stand characteristics in order to minimize damage to forests. Understanding the relationships between topographic and stand characteristics and windthrow areas can help preserve the biological structure of forests and provide guidance to forest managers.

Keywords: Stand, Forestry, Windthrow, Topography, Türkiye

Topoğrafya ve Meşcere Yapısının Rüzgâr Devriği Zararlarına Etkisinin Araştırılması: Düzce Orman İşletme Müdürlüğü Örneği

Öz

Çalışmanın amacı: Araştırmanın amacı, rüzgâr devrik alanlardaki ağaç hacmi ve hasar düzeyini belirlemek ve topografik faktörlerin ve orman yapısının rüzgâr devriğine olan etkisini değerlendirmekti.

Çalışma alanı: Çalışmamız Düzce Orman İşletme Müdürlüğü sınırları içinde gerçekleştirildi.

Materyal ve yöntem: Düzce Orman İşletme Müdürlüğü sınırları içindeki rüzgâr devrik alanları, olağanüstü verim raporlarından elde edildi. Google Earth kullanılarak doğrulanan rüzgâr devrik verilerine göre her bir hasara ait sınır belirlendi ve ArcMap'e aktarıldı. Rüzgâr devrik alanları ile çevresel parametreler arasındaki ilişkiler, dijital haritalar ve orman amanejman planları kullanılarak belirlendi. Rüzgâr devrik alanları ile topoğrafik ve orman özellikleri arasındaki ilişkiyi tespit etmek için korelasyon analizi uygulandı. Ayrıca, rüzgâr devrik alanları ve miktarları ile hâkim bakı ve orman türleri açısından farklılık olup olmadığını belirlemek için varyans analizi yapıldı. Rüzgâr devrik alanları ve miktarları ile hâkim rüzgâr yönü arasındaki farklılıkları belirlemek için T-testi uygulandı. İstatistiksel olarak anlamlı bulgulara dayanarak, çevresel parametrelere intersect analizi uygulanıp rüzgâr devrik uygunluk haritası oluşturuldu.

Temel Sonuçlar: Rüzgâr devrikleri çoğunlukla güneybatı yönünde, Göknar-Kayın türlerinde ve c-d yaş sınıflarında meydana geldi. Rüzgâr devrik alanı ile ağaç çapı ve yükselti arasında istatistiksel olarak anlamlı bir ilişki ($p<0.05$) bulundu ve aynı şekilde rüzgâr devrik miktarı ile yükselti ve sit endeksi arasında da anlamlı bir ilişki tespit edildi. Ayrıca, rüzgâr devrik alanında hâkim yön grupları ve tür karışım sınıfları ile anlamlı ilişkiler ($p<0.05$) bulunmuştur.

Araştırma vurguları: Rüzgâr devriği hasarı dinamik bir süreçtir. Bu süreçte ormanların en az zarar görmesi için topografik ve meşcere özellikleri ile ilişkilerinin belirlenmesi önemlidir. Topografik ve meşcere özellikleri ile rüzgâr devrik alanlarının ilişkilerinin tespit edilmesi, ormanlardaki biyolojik yapıyı korumak ve orman yöneticilerine rehberlik etmek için önemli olacaktır.

Anahtar Kelimeler: Meşcere, Ormancılık, Rüzgâr devriği, Topoğrafya, Türkiye

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Introduction

Among the functions of forests, which are one of our most important natural resources, are water protection, soil conservation, and biodiversity preservation (Akbulak & Özdemir, 2008). In order to ensure the continuity of these functions, forests need to be planned, taking into account social, economic, environmental, and sociocultural factors (Wilkie et al. 2003). In recent years, biotic and abiotic factors that affect forests have had a significant impact on the sustainability of forest resources and have caused significant biological and ecological damage to vegetation. Abiotic factors include forest fires, storms, snow, avalanches, and drought (Torun & Altunel, 2020; Baggio et al. 2022; Cooke et al. 2022; Çınar et al. 2023).

Sustainability, the fundamental pillar of forestry, emerges as an unparalleled concept. This principle aims to produce the maximum amount of timber and non-timber forest products from forests, while simultaneously ensuring the highest level of utilization of the collective functions of forests, within the limits allowed by the existing natural conditions. In order to speak of sustainability, it is essential for the forest presence in a given area to be continuous. As in the rest of the world, in Turkey, one of the factors that jeopardize the sustainability of forests is wind, storms, and snowfall causing tree falls. It is known that the result of tree falls occurring annually due to various reasons leads to the disappearance of thousands of hectares of forest areas, resulting in significant damage to climate and water regimes, as well as causing erosion and flooding disasters (Canakcioglu, 1993; Abram et al. 2021; Zhao et al. 2013)

The forest, composed of organic matter and a living entity, is exposed to various hazards caused by both biotic and abiotic factors until it reaches the maturity, due to its open nature. The protection of forests can only be achieved by rendering harmful factors harmless. Therefore, it is crucial to have a good understanding of these factors and then eliminate the underlying causes that give rise to them. The expected benefits from the forest can only be obtained if it is well protected, ensuring sustainability (Paluš et al. 2018; Bamwesigye et al. 2020)

Storms and windthrow which have a negative impact on forest sustainability are significant issues in European forestry particularly in plantation areas, like in Turkey. In December 1999, a storm in France caused significant damage to forests, resulting in an estimated €8.5 billion in losses across all sectors. In the forests of England, 1 million m^3 of trees fall annually due to storms. In Germany's Black Forest region, the number of windthrow caused by the storm in 1999 was three times higher than the annual production volume (Schmoeckel et al. 2003).

When looking at examples in Türkiye, it is stated that the largest windthrow occurred between 1955 and 1964 in the Bolu (together with Zonguldak Forest Regional Directorate) and Kastamonu (together with Sinop Forest Regional Directorate) Regional Forest Directorates. It can be concluded that the damage that occurred in these four regional directorates was a unique event specific to the Western Black Sea Region. The damage that occurred in the four regional directorates has resulted in a total of 2321632 $m^3$of tree loss in the forest. The strong wind that occurred on 26-27 February 2001 in the Aydınpınar region of Düzce affected dozens of poplar plantations; breakage, windthrow, tilting on its side, etc. was reported to have caused various damages (Yavuzşefik & Çetin, 2002).

Storm damage can cause significant damage, especially in forested areas. These damages include the harm destruction of trees, the dangerous nature of salvage, and issues related to vehicles, personnel, and storage locations in the production process. Furthermore, the conditions resulting from windthrow can be highly dangerous, making occupational safety the primary objective. These conditions carry a high risk of injury and fatality (Fukui et al. 2018). Following windstorms, extensive afforestation efforts take place in large areas, which may disrupt transportation, and new wood up facilities are established promptly to minimize delays. (Engür, 2006; FAO, 1995). The aim of this study is to: (1) obtain information about the volume of trees and the extent of damaged areas caused by windthrow incidents in the Bolu Forest Regional Directorate (Bolu-Düzce provinces), (2) identify the information regarding the damaged trees in the windthrow areas of the Düzce Forest Management Directorate, (3) investigate the influence of topography and stand structure on windthrown damages, and (4) provide suggestion for reduce of the windthrow damages.

The storm occurrence of thousands or even millions of cubic meters of windthrow damage in forested areas, resulting in unexpected and undesirable consequences, is an undesirable situation for forest management (Engür, 2006). In the past, severe storm damage have occurred in many European countries, particularly in Northern and Central Europe, as well as in Turkey. For example, Torun (2018) indicated that in the Kastamonu Regional Directorate of Forestry, a damage of 1.5 million cubic meters occurred in an area affected by a storm.

According to climate scientists, storms and winds that cause the effect of wind will occur more frequently by the year 2050 compared to the present day (García-Casals, 2008; Jandl et al., 2009). Adequate preparation is necessary to mitigate the damages caused by windthrow. The better the preparation, the greater the success in minimizing and effectively managing such a disaster. Windthrows pose several challenges in the forest products market by disrupting the supply-demand balance. They necessitate the implementation of mandatory reforestation programs, lead to changes in wildlife dynamics, alter the visual landscape in recreational forests, hinder the activities of beneficiaries, result in road closures and transportation disruptions in mountainous areas, occasionally trigger insect infestations due to drying and dead trees, and cause value losses in timber due to fungal and bacterial activities (Engür, 2006). Storms and hurricane can cause damage to trees, leading to breakage, cracking, or deformation, which results in economic and quality-related losses in forest products. Additionally, the damage incurred can lead to economic losses in regeneration areas and even necessitate the revision of management plans (Einzmann et al., 2017; Klaus et al., 2011). Storm damage in the forest also eliminate the ecological protection provided by the forest, giving rise to weed invasion, pest damage, and increased fire risks (Canakcioglu, 1993).

Strong winds with an average speed of 20 m/s are referred to as storms. Although storms may seem similar to regular winds, their impact on forests is significantly different due to the substantial damage they cause. They particularly result in severe material damage to coniferous tree species. In needle-shaped leaf tree species, storms loosen the tree from its roots and cause it to bend and fall. The strength of the tree roots to withstand the destructive effects of the wind determines the extent of damage, which can be observed as stem breakage and crown damage. Storms often cause damage not only individually but also to groups of trees or even entire forest stands (Acatay & Gülen, 1971; Senf & Seidl, 2021). The extent of storm damage varies depending on the intensity, speed, and duration of the storm (Canakcioglu, 1993; Zhang et al. 2011). Damage to trees includes uprooting, breakage, tilting, and crown damage.

The most important factors that influence the magnitude of the windthrow effect on forest trees during storms include tree species, age, canopy density, site index (Scott & Mitchell, 2005), topographic characteristics (slope, aspect, elevation) (Lanquaye-Opoku & Mitchell, 2005), soil depth (Kooch et al. 2014), prevailing wind direction and intensity of precipitation (Taylor et al. 2019).

Topographic Factors: The wind direction and speed that are effective in the damage caused by windthrow are related to the topographic characteristics of the location of the damaged trees (Lanquaye, 2003). In all the studies on storm damages, elevation, slope and aspect parameters from general topographic features were evaluated (Kramer et al., 2001; Quine, 1995).

In a study mentioned in (Schmoeckel et al., 2003), it is shown that windthrow at low altitudes (<150 m) is less than at high altitudes (1000 m), but at higher altitudes the trees are subject to adverse weather conditions and that its resistance to storms was higher because its adaptability to other ecological influences was quite good. However, it has been seen in the mentioned study that most of the windthrow risk occurring is in the 20-30% slope range, and where the slope is less than 20%, the damage is less. At the same time, it has been determined that the storm damage is much less in the lands where the slope is very high. Accordingly, in the studies conducted in (Schütz et al., 2006), it was determined that there was an inverse proportion between the slope and the windthrow damage.

According to the dominant aspect, it was seen that the north, northwest and southwest aspects were more affected by the windthrow damage, and the northeast, south, west and east aspects were also affected by this damage, respectively (Schmoeckelet & Kottmeier, 2008).

Stand properties; evergreen needle species are more vulnerable to storms than broadleaved species (Skłodowski, 2020; 2023). Broadleaved speicies are resistant to storms because their wood is relatively stronger and have taproots (Vašutová et al., 2018). Furthermore, broadleaved and needle mixed stands are more resistant to windthrow damage (Jactel et al., 2017).

The risk of windthrow damage increases with age (Atay, 1987; Foster, 1988). Mostly windthrow damage is seen in stands older than 45-50 years. Accordingly, with this, trees with root rot and some stem diseases are also affected by windthrow damage. Since trees that are short and flexible are in the majority in stands that are not too old, the probability of windthrow is less. However, in species with shallow roots, storm damage can be seen more than expected in cases where storm intensity is too high and where soil structure is weak (Dragoi & Barnoaiea, 2018; Hanajík et al., 2017).

Since root and crown development is not sufficient in trees with intricate stand coverage, their resistance to storms is less compared to trees in stands with less canopy (Einzmann et al., 2017). The protection and attachment of trees in the intricate closed stands is due to the trees acting as a curtain on the edge of the stand. If hurricane enter the stand from any direction, it means that the stand will be unprotected (Ivanova & Shashkov, 2022). For this reason, trees grown individually are more resistant to hurricane due to their root, stem and crown structures (Mitchell & Ruel, 2015; Ver Planck & MacFarlane, 2019).

The concept of site index can also be defined as the quality and efficiency of the product produced or the service rendered. Where the site index is different, the percentage of yield will also be different. Yield increases in places with good site index (Gáfriková et al., 2019). A positive relationship was found between windthrow damage and site index (Cucchi et al. 2005). As the site index increases in the same aged stands, windthrow damage increases due to the increase in yield and volume (Meng et al., 2017). In some studies, it has been determined that the height and diameter ratio is a factor that increases the danger of windthrow damage. Therefore, the increase in the rate increases the danger of windthrow (Vodde et al., 2010; Lavoie et al., 2012).

Considering the soil structure, which is stated as another factor, if there is water accumulation at the bottom in impermeable and shallow soils, it is inevitable that the windthrow will increase. At the same time, soild that are wet due to previous rain and saturated with water are also fators that cause windthrow (Vodde et al., 2010; Negrón-Juárez et al., 2017). While the resistance of tree roots to windthrow increases in forest soils with a high proportion of compacted sand, it decreases in soils with a high clay content due to the inability of the roots to adhere well to the soil (Lavoie et al., 2012; Dos Santos et al. 2016). In forests with well-permeable and non-shallow soils, the roots are strong and resisitant to windthrow (Steil et al., 2009). In addition, windthrow damage is higher in forests in areas where the mineral substances in the soil are insufficient and the soil structure is loose (Šamonil et al., 2008; Don et al., 2012).

Climate factors; the prevailing wind direction and strength is the most important climatic factor that can cause windthrow. Hurricane of up to 55 km/h and more are capable of causing serious damage. If the effect of hurricane lasts a long time, the tree roots will be damaged more and the size of the damage will increase. It is precisely at this time that the accumulation of snow and the formation of frost from heavy snowfall cause fractures and windthrow of the trunk as it will increase massively in the crown (Byrne & Mitchell, 2013).

Loose soil in areas exposed to sustained and heavy rainfall before hurricane leads to increased windthrow damage (Jack et al., 2014; Constantine et al., 2012). Water-saturated soil caused by melting snow also causes windthrow. Thus, the effect of seasonal causes on windthrow is proven. (Matiu et al., 2017; Hartmann et al., 2015).

Material and Methods

Study Area

In the study, the windthrow areas between 2015-2018 within the borders of Düzce Forestry Management Directorate were examined in terms of topography and stand structure. In Düzce Director of Forest District, it consists of 54090 ha of normal forest area, 1738 ha of degraded forest area and 63823 ha of non-forested land. Düzce Director of Forest District is located in the inner part of the Western Black Sea section and consists of 14 directorate of forest district. As a geographical coordinate; It is located between 31° 28' 54"- 30° 46' 45" - 31° 16' 44"- 31° 11' 31" East longitudes and 40° 47' 35" - 40° 52' 13"- 40° 59' 49"- 40° 37' 20" North latitudes. The forests within the borders of Düzce Director of Forest District generally manifest themselves in drought and harsh climatic conditions, which are the climatic features of the Central Anatolian climatic zone. The main tree species of the region are Eastern Beech (*Fagus orientalis* Lipsky.), Uludag Fir (*Abies nordmanniana* subsp. bornmülleriana Mattf) and Scotch Pine (*Pinus sylvestris* L.). According to the Düzce Meteorological Station, the average annual rainfall is 840 mm, the average temperature is 13°C. (GDM (General Directorate of Meteorology), 2022). Figure 1 shows the location of Düzce Director of Forest District in Turkey and the windthrow areas. In the study, a study form containing information on the topographic and some stand characteristics of the windthrow areas was created.

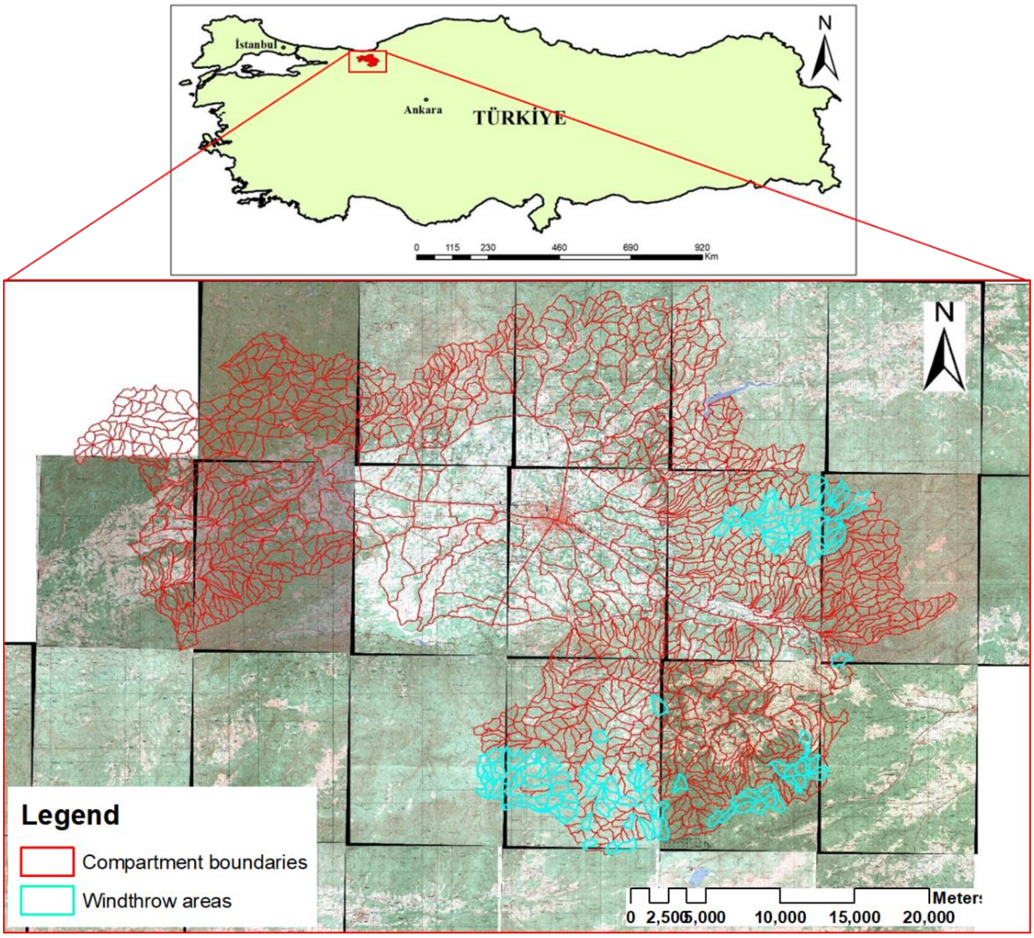

Figure 1. Düzce director of forest district location and windthrow areas (31° 10′ 0″ East longitudes and 40° 49′ 59″ North latitudes) map

Method

In this study, data pertaining to the Düzce Director of Forest District were collected from various sources, including the Bolu Regional Directorate of Forestry Conservancy, Regional Forest archive, and windthrow extraordinary yield reports of previous years. However, only the registered reports from 2015 to 2018 (a span of 4 years) could be accessed, and thus, the study focuses on this timeframe. Proper permissions were obtained to utilize this data, and relevant pages were photographed for reference.

Initially, the windthrow amounts within the Düzce Director of Forest District were calculated on an annual basis using the data extracted from the photographed reports. This allowed for the determination of windthrow amounts within the Düzce directorate, which were subsequently incorporated into the study's framework.

To identify windthrow areas (based on topographic data) and storm damaged tree information (pertaining to certain stand structures) in the Düzce Director of Forest District, imagery from Google Earth, management plan maps, and topographical maps were utilized (Figure 2). Both graphical and attribute data related to the research area were acquired and organized within a GIS database. A 3D land model was constructed to analyze the topographic structure of the land. To achieve this, a contour maps was used, with each contour's elevation value entered into the attribute table of the digitized layer. A digital terrain model was generated from the contour layer, enabling the determination of slope, aspect, and elevation of the research area.

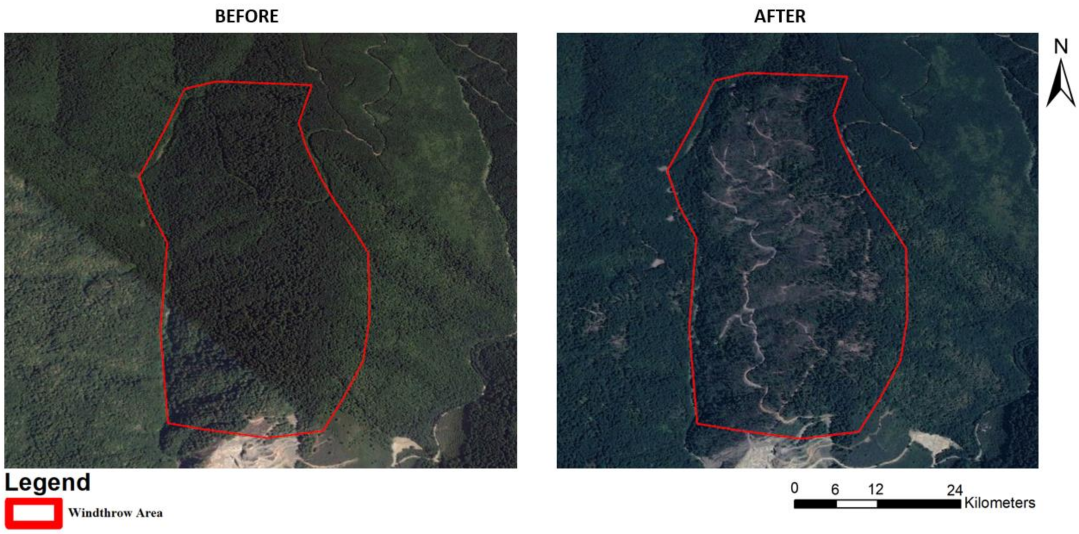

Figure 2. Verification of windthrow areas in data obtained from extraordinary yield reports using Google Earth Imagery

Determination of stand features

The characteristics of the stand, including average slope, aspect, and elevation, were obtained from the GIS database, which contains information from the reports of extraordinary yield and the management plans of the forest directorate.

Other stand characteristics such as site index, stand development stage, cover, and prevailing wind direction were acquired from the management plan data. The management plans provide valuable information regarding the forest composition, growth, and management strategies in the study area.

By combining the data from the extraordinary yield reports, management plans, and GIS database, a comprehensive understanding of the stand characteristics was achieved for the analysis conducted in the study. These data sources allowed for a detailed examination of the relationship between windthrow and various stand and topographic factors.

Statistical methods used

The normality of the data was assessed using the Kolmogorov-Smirnov normal distribution test. For data that did not follow a normal distribution, appropriate transformations were applied to ensure a normal distribution.

Correlation analysis was conducted to examine the relationship between the windthrow area and amount, as well as various topographic factors such as slope and elevation, and stand characteristics including tree diameter, cover, and site index.

Furthermore, analysis of variance (ANOVA) was performed to determine if there were differences in windthrow areas and quantities based on prevailing aspect and species mix. Additionally, an independent sample t-test was employed to assess whether there were differences in windthrow areas and quantities based on the prevailing wind direction.

In the analyses, the average diameters of the stand development stage classes were used to represent tree diameters, and lg10 conversion was applied to achieve a normal distribution of the windthrow amount. All statistical analyses were conducted using the SPSS 22 package program.

Intersect analysis

Maps related to the parameters highly significant reliationship with windthrow were generated based on the statistical results applied to environmental parameters. Suitability maps were produced using intersect analysis on the generated maps. According to the intersect analysis results, areas where windthrow may occur within the Düzce Forest Management Directorate were detected.

Results and Discussion

Results on Study Area Windthrow

The study analyzed the windthrow extraordinary yield reports from the years in the Bolu Conservancy, Regional Forest archive. Specifically, the data from the Düzce Director of Forest District between 2015 and 2018 were examined. The total windthrow damage encountered in this period was 838.36 m³. Among the different directorates, the highest windthrow damage occurred in the Aksu Director of Forest District, while the lowest occurred in the Darıyeri Director of Forest District (Table 1).

The storm damages were observed in 48 distinct locations within the Düzce Director of Forest District. Interestingly, 26 of these windthrows recurred in the same areas at different times, indicating a pattern of windthrow occurrence.

Table 1. Storm damage yield report amounts under the Düzce Director of Forest District

Forest District \ Years	2015	2016	2017	2018	Total (m³)
Aksu			35478	12872	48350
Asar	2293			693	2986
Cumaova					
Darıyeri				24	24
Düzce			71		71
Konuralp					
Melen					
Odayeri	21944	174		1015	23133
Samandere	98	2722	321		3141
Tatlıdere				2.675	2.675
Total (m³)	24335	6119	36103	17279	83836

Results on the Impact of Windthrow Damages on Topography

Table 2 presents the results of certain topographical and stand data obtained in the study. The average values recorded in this table include a tree diameter of 26 cm, a canopy cover of 3, a site index of II, a slope of 41%, an elevation of 1154 m, a windthrow area of 37 ha, and a windthrow amount of 631 m³.

In a study conducted by Schütz et al. (2006), an inverse relationship was observed between slope and windthrow damage, with the highest risk occurring in the 20-30 %slope range. However, in the present study, windthrow damages occurred at an average slope of 41%, and no significant relationship was found between slope and windthrow.

Previous studies have indicated that trees with complex stand occupancy, lacking sufficient root and crown development, are more susceptible to wind damage compared to trees in stands with less canopy cover (Mitchell, 2000). Additionally, the presence of trees along the stand edges acts as a protective barrier. When hurricanes or strong winds enter the forest from any direction, stands without such edge trees become more vulnerable. Therefore, individually growing trees exhibit greater resistance to wind damage due to their root, trunk, and crown structure (Canakcioglu, 1993; Atay, 1987). However, in the present study, windthrow damages predominantly occurred in areas with a canopy cover of 3 (71%-100%), and no significant relationship was found between canopy cover and windthrow.

Studies investigating windthrow damages have highlighted the influence of wind intensity and speed, as well as the topographic characteristics of the affected trees, particularly aspects, slopes, and elevations (Lanquaye, 2003; Quine, 1995). In the study area, windthrow areas were predominantly located in the west, southwest, and southeast aspects. The windthrow amounts recorded were 3551 m³ for the western aspect, 54477 m³ for the southwest aspect, and 37928 m³ for the southeast aspect, indicating that the most significant windthrow occurred in the southwest aspect (Figure 3). However, a previous study by Schmoeckel et al. (2003) reported that windthrow damage was more prevalent in the northern, northwestern, and southeastern aspects. This difference could be attributed to the dominant aspects in the study area not aligning with the northern and northwestern aspects mentioned in the previous study.

Table 2. Characteristics of the study area topographic and stand data

Parametreler	Compartment Number	Lowest	Highest	Average
Diameter (cm)	105	4.00	44.00	25.94
Cover (%)	152	1 (10%-40%)	3 (71%-100%)	3 (71%-100%)
Site index	152	IV	I	II
Slope (%)	152	20.00	73.00	41.24
Elevation (m)	152	400.00	1650.00	1153.95
Area (ha)	152	1.00	94.00	37.50
Amount (m³)	152	18.00	12468.00	631.29

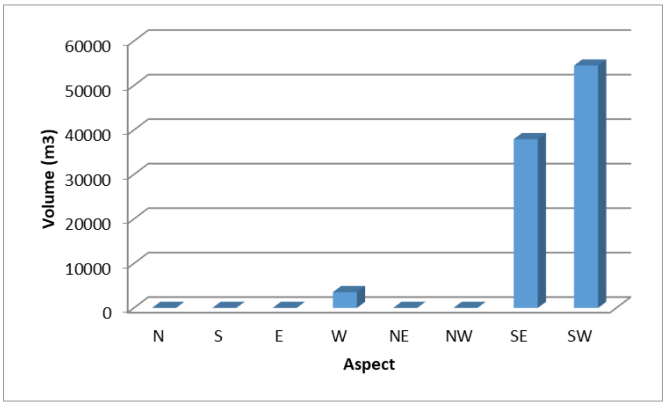

Figure 3. The amount of windthrow that occurs according to the prevailing aspect in the study area

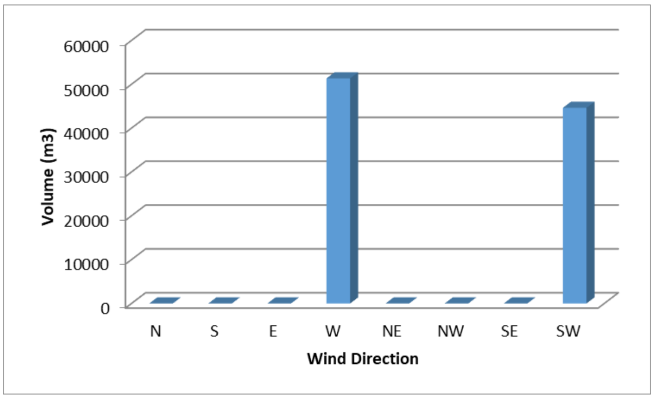

Figure 4. The amount of windthrow that occurs according to the prevailing wind direction in the study area

Results on the Impact of Storm Damage on the Structure of the Stand

In the study area, windthrows were observed in 27 different species and species mixtures specific to the region. The highest occurrence of windthrow was recorded in areas dominated by Fir-Beech (G, Kn) tree species (30439 m³), while the lowest occurrence was found in areas with Beech-Fir-Hornbeam (Kn, G, Gn) and Beech-Linden-Other Leafs (Kn, Ih, Dy) tree species (170 m³) (Figure 5).

Regarding species mixtures, windthrow was most prevalent in pure-leaf stands and least prevalent in softwood stands (Table 3). However, previous studies have suggested that needle species (evergreen species) are more vulnerable to storms compared to broad-leaf species (Canakcioglu, 1993; Acatay & Gülen, 1971; Atay, 1990; Foster & Boose, 1995). Additionally, mixed stands with a combination of needle and broad-leaf species or pure needle stands have shown higher resistance to windthrow damage (Acatay & Gülen, 1971). Studies conducted by Jactel et al. (2017) and Bauhus et al. (2017) have identified that mixed forest areas have a higher resistance to windthrow. In our study, it was possible to concluded that windthrow areas cause less damage in forests with a mixed forest structure. In addition to the conducted studies, it was important to emphasized that the intensity and speed of the wind played a crucial role in windthrow damaged.

In the present study, the highest amount of windthrow was observed in stands with the development stage of cd, while the lowest amount was found in stands with the age of ab (Table 3).

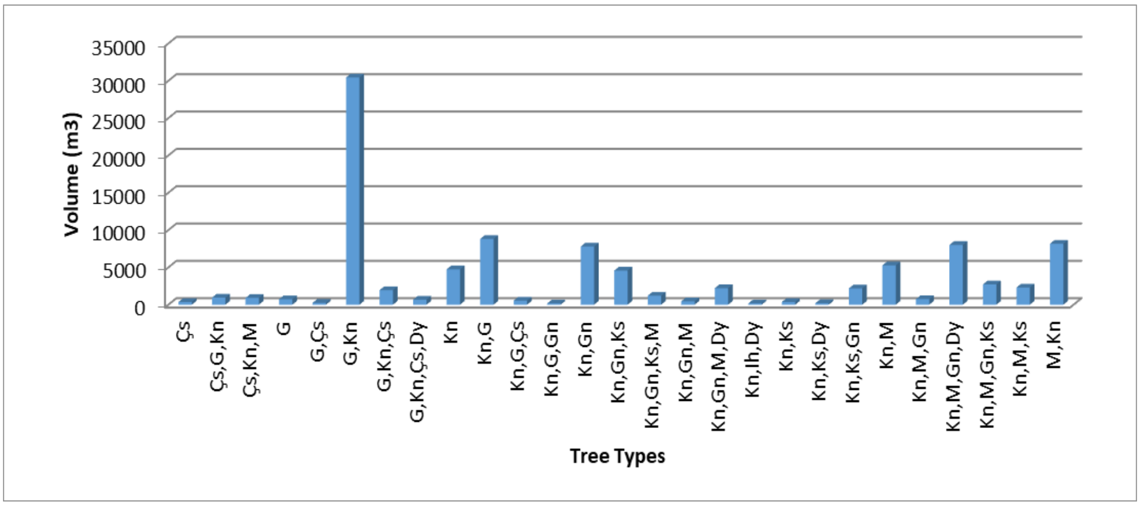

Figure 5. The amount of windthrow that occurs in the study area according to species and type mixtures

Table 3. Results on the stand development stage and species mixing in the area of study

Parameters		Area (ha)	Amount (m³)
Stand development stage	a (dbh 0 cm – 7.9 cm)	1234	5345
	ab (dbh 0 cm – 19.9 cm)	0	0
	b (dbh 8 cm – 19.9 cm)	134	2055
	bc (dbh 8 cm – 35.9 cm)	217	13625
	c (dbh 20 cm – 35.9 cm)	580	7978
	cd (dbh 20 cm – > 51.9 cm)	431	32119
	d (dbh 36 cm – > 51.9 cm)	655	4439
	d/a (Multi-stemmed tree ((d/ dbh 36 cm – > 51.9 cm) a/ (dbh 0 cm – 7.9 cm))	2449	30395
Type mixture	Needle	3157	34007
	Pure needle	346	1335
	Pure leaf	1084	51092
	Leaf -needle	1113	9522

Results on statistical analyses

In the correlation analysis, a statistically significant relationship was found between the windthrow area and tree diameter (rs=-0.363) (Figure 6). Another different study was conducted by Mayer et al. (2014), Mayer et al. (2014) in the research windthrow area related with stand development stage. It was results showed that windthrow area high related with stand development stage. In a different study Wohlgemuth et al. (2017) where the relationship between environmental factors and windthrow areas was determined, it was found that there is a high level of correlation between stand development stage and windthrow areas. Addition, it was indicated that previous studies have indicated that the risk of windthrow damaged typically increases with tree age and younger stands with shorter and more flexible trees tend to be less susceptible to windthrow (Atay, 1987; Moore, 2000). Nevertheless, in shallow-rooted species, particularly in areas with high storm intensity and poor soil structure, windthrow damage can be more prevalent than expected (Jeon et al., 2015).

Our study showed that despite the expected trend, a contrary result was obtained with the highest windthrow area observed in the stand with the highest development stage (cd). This discrepancy may be attributed to the speed and intensity of the wind, which can influence the vulnerability of trees to windthrow.

On the other hand, a significant positive correlation was found between the windthrow area and elevation (r_s=0.514) (Figure 6) (p<0.05). No statistically significant relationships were found with other data.

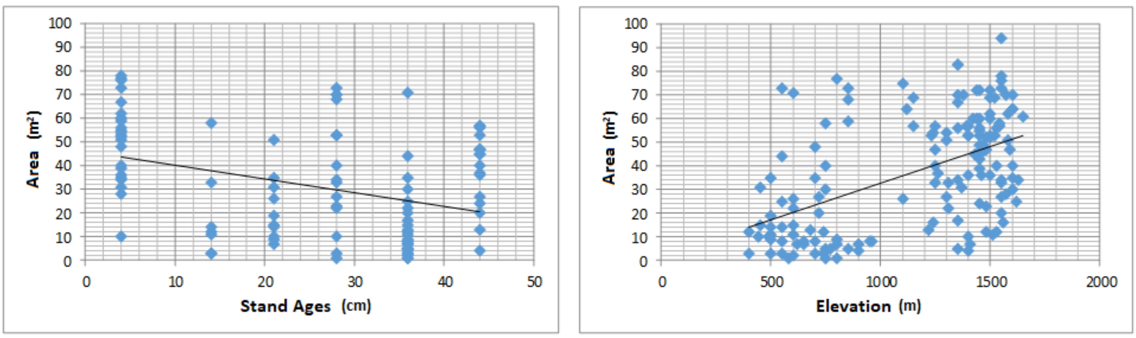

Figure 6. Correlation between windthrow area stand development stage and elevation

Furthermore, a statistically significant negative relationship was observed between the amount of windthrow and elevation (r_s=0.354) (Figure 7). This finding aligns with a study conducted by Schmoeckel et al. (2003), which revealed that windthrow occurrences are less frequent at lower elevation (<150 m) compared to higher elevation (1000 m). Trees at higher elevation tend to be well adapted to adverse weather conditions and other ecological factors, resulting in greater resistance to storms (Freitas et al., 2023; Abuseif et al. 2022). This study's findings support that trend, indicating that as elevation increases, the amount of windthrow decreases.

Additionally, a statistically significant positive correlation was found between the amount of windthrow and the site index (r_s=0.198) (Figure 6) (p<0.05). Similar results have been reported in previous studies by Harris (1989) and Jull (2001). According to, Harris (1989) and Jull (2001) have highlighted that there was more windthrow damage to forest areas with site indexes of I and II. In diffirent study by Cucchi et al. (2005) was detected windthrow area relation with site index in the forest area. Cucchi et al. (2005) for the reliation between site index and windthrow use the GALES model. According to the model results, Cucchi et al. (2005) detected that there was more windthrow damaged in forest areas with a site index of I. According to in our study the correlation analysis results, it has been determined that windthrow is more widespread in areas with a site index of I and II.

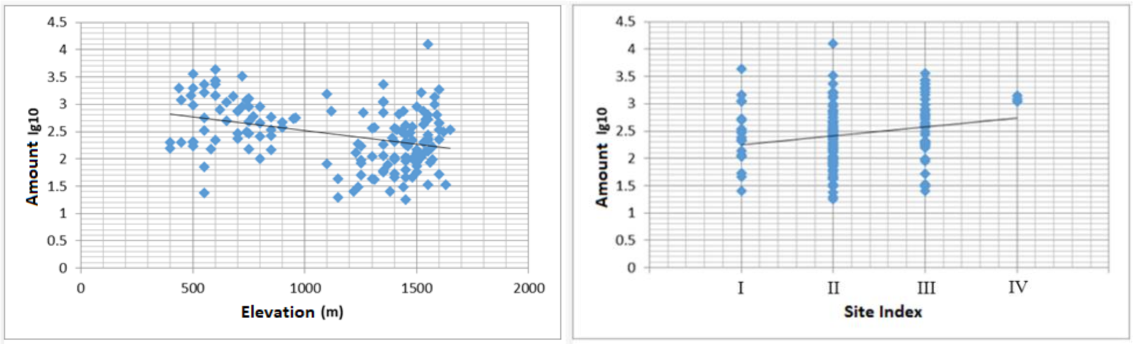

Figure 7. Correlation between windthrow amount Elevation and Site Index

A t-test was conducted to examine the difference between windthrow area amounts and the prevailing wind direction. The results indicated that there was no statistically significant difference (p<0.05) in terms of windthrow areas and amounts based on the prevailing wind direction. It is possible to find the research conducted by Ruel et al. (2001) and Bouchard et al. (2009) regarding the determination of the importance of prevailing wind direction in wind-prone regions. In their research, Ruel et al. (2001) and Bouchard et al. (2009) have determined that the prevailing wind direction does not play a significant role in the occurrence of windthrow. This study supports the findings of Ruel et al. (2001) and Bouchard et al. (2009). The prevailing wind direction in the study area was determined to be west and southwest aspects. This suggests that the windthrow area and amount did not vary significantly between these two wind directions.

Regarding the analysis of variance, a statistically significant difference ($p < 0.05$) was found between windthrow areas in dominant aspect groups and species mixture classes. The windthrow areas were highest (51307) in the southeast, lowest (25842) in the southwest, and different from both in the west (39643). Windthrow areas were in the same group as pure needle, pure leaf, and leaf-needle, but in a different group from needle-leaf. Among these groups, leaf-needle had the highest windthrow area (52207), while needle-leaf had the lowest (20.328). Additionally, the amount of windthrow was highest (2582) in the southwest, lowest (2167) in the west, and intermediate (2330) in the southeast. In terms of species mixture classes, the amount of windthrow was highest (2663) in needle-leaf, lowest (2167) in leaf-needle, and pure needle and leaf-needle showed similarity (Table 4). The study has concluded that windthrow may be more prevalent in forest species with a leaf-needle structure, based on aspect categories. Mayer (1989) identified the greater susceptibility of leaf species to windthrow in his study. In a separate study, Gross (2018) emphasized that locations dominated by leaf species may also be more vulnerable. However, it is possible to assert that windthrow is more common in the needle-leaf category when considering species mixture classes that do not include directional factors. Studies conducted by Dalponte et al. (2020) and Thürig et al. (2005) have documented a higher occurrence of windthrow in the needle-leaf category in the literature. Nevertheless, it is worth noting that windthrow can occur in all species mixture classes, as indicated by research conducted by Peterson and Pickett (2000) and Peterson and Leach (2008).

Table 4. Variance analysis results of windthrow areas and their amounts

Parameters	Parcel	Mean	Standard eror	*p**
Windthrow area	W	39643 a	5.574	
	SE	51307 b	2.546	0.000
	SW	25842 c	2.506	
Windthrow area	NL	20328 a	2.563	
	PN	39778 b	8.031	0.000
	PL	47304 b	2.834	
	LN	52207 b	3.196	
	W	2167 a	0.132	
Windthrow amount	SE	2330 ab	0.077	0.004
	SW	2582 b	0.056	
	NL	2663 a	0.067	
Windthrow amount	PN	2291 b	0.076	0.000
	PL	2378 ab	0.081	
	LN	2167 b	0.081	

* *p* 0.05 W West. SE southeast SW southwest NL needle-leaf PN pure needle PL pure leaf LN leaf-needle leaf-needle

Maps of important parameters affecting windthrow and results of the intersect analysis

In the analyses conducted at the Düzce Forest Management Directorate, areas with a site index of '0' have been excluded. This is because areas with a site index of '0' do not contain forests. For our study, slope, aspect, elevation and stand development stage very important parameters in windthrow areas. Aspect, elevation, slope, and stand development stage maps related to the Düzce Forest Management Directorate are displayed in Figure 8.

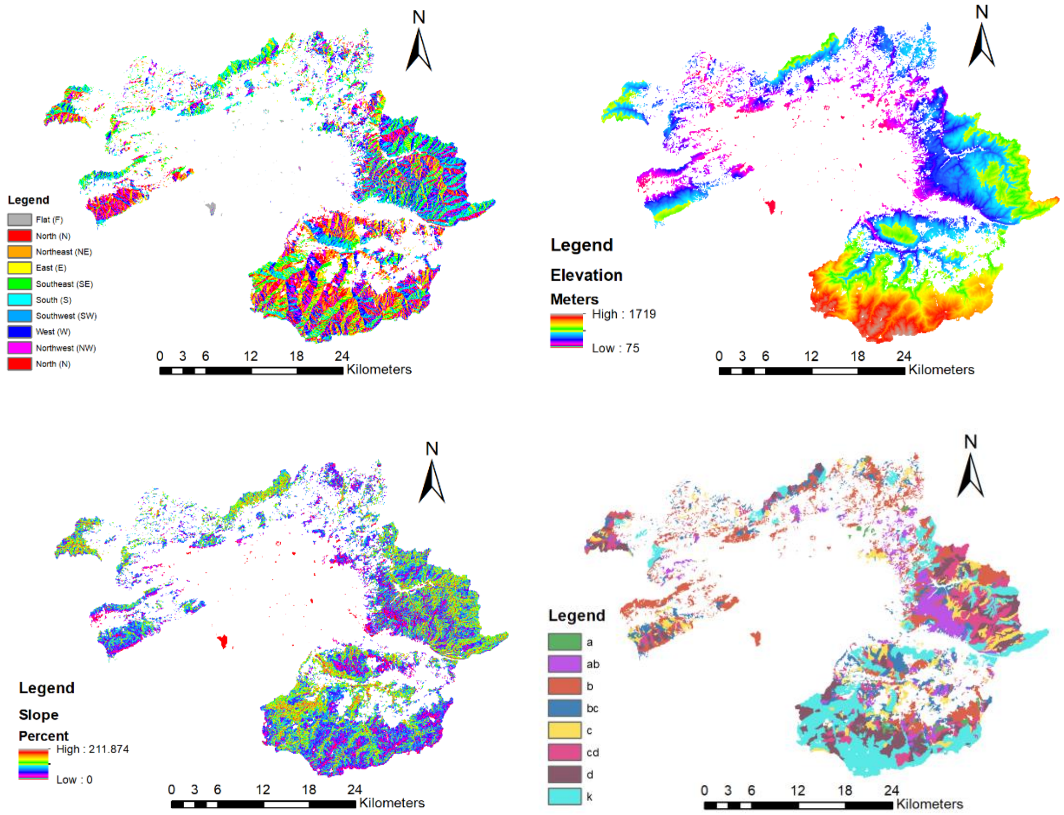

Figure 8. Aspect, elevation, slope, and stand development stage maps belonging to the Düzce Forest Management Directorate

In the Düzce Forest Management Directorate, intersect analysis has been applied to the most important parameters affecting windthrow areas which include slope, aspect, elevation and stand development stage. According to the results of the intersect analysis, it was determined that there is a high windthrow in Aksu, Samandere, Odayeri, Darıyeri and Tatlıdere. The results of the intersect analysis applied to the important parameters are presented in Figure 9.

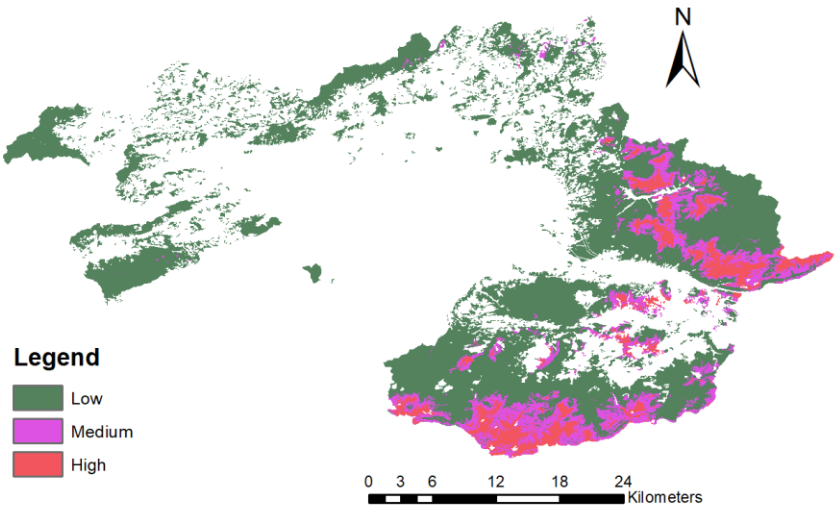

Figure 9. Intersect analysis results for windthrow areas in Düzce Director of Forest District

Conclusion

In the study, the reports from the years 2015-2018, which focused on the Düzce Director of Forest District, were coniferrous and deciduous examined. A total of 83836 m^3 of coniferous and deciduous species have examined windthrow. The windthrow incidents in the directorate were found to have occurred in 48 different independent areas, with 26 of them experiencing recurring incidents at different times. The dominant wind directions were determined to be west and southwest.

Regarding the topographic data in the study area, it was found that the average slope of the windthrow areas was 41%, with an elevation of 1154 m. The dominant aspects were west, southwest, and southeast, with the southwest aspect experiencing the most windthrow.

The study also investigated the impact of stand structure on windthrow damage. It was discovered that there were 27 different species and species mixtures in the area. Fir and Beech were found to be the most damaged tree species in the region, respectively. The most damaged stand development stage was identified as cd, with the species mix being pure leaf stands.

Statistical analysis revealed several correlations. There was a statistically significant negative correlation between the windthrow area and tree diameter (r_s=0.363), and a positive significant correlation between the windthrow area and elevation (r_s=0.514). Furthermore, a statistically significant negative correlation was found between the amount of windthrow and elevation (r_s=0.354), while a statistically positive correlation was observed between the amount of windthrow and site index (r_s=0.198).

Regarding windthrow areas, analysis of variance demonstrated a statistically significant difference between dominant aspect groups and species mixture classes. Similarly, in terms of the amount of windthrow, a significant difference was observed between dominant aspect groups and species mixture classes.

It is crucial to integrate windthrow damage into management plans while maintaining the principles of sustainability. Preparations should be made in advance to minimize windthrow damage, enabling managers to respond promptly and make informed decisions. Additionally, transportation and work safety planning should be carried out meticulously during windthrow harvesting studies.

Furthermore, to minimize windthrow damage, it is essential to identify the most important factors contributing to these incidents and develop windthrow susceptibility maps.

Ethics Committee Approval

N/A

Peer-review

Externally peer-reviewed.

Author Contributions

Conceptualization: Y.T., H.Ç.; Investigation: Y.T., H.Ç., T.Ç., A.A.; Material and Methodology: Y.T., H.Ç., T.Ç., A.A.; Supervision: Y.T., A.A.; Visualization: H.Ç., T.Ç.; Writing-Original Draft: Y.T., H.Ç., T.Ç., A.A.; Writing-review & Editing: Y.T., H.Ç., T.Ç., A.A.; Other: All authors have read and agreed to the published version of manuscript.

Conflict of Interest

The author has no conflicts of interest to declare.

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