137. Jahrgang (2020), Heft 1, S. 1–22

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

Modeling wind-driven tree mortality: the effects of forest roads

Modellierung der durch Wind verursachten Waldsterblichkeit: die Auswirkung von Forststraßen

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Keywords: *beech, hornbeam, Fagus orientalis, Carpinus betulus, disturbances, gap dynamics*

Schlüsselbegriffe: *Buche, Hainbuche, Fagus orientalis, Carpinus betulus, Störungen, Gapdynamik*

Abstract

Strong wind is an important natural disturbance in temperate forests causing damage, stand gaps, soil disturbance and changes in vegetation composition. The aim of the current study was to assess the effect of forest roads as man-made infrastructures on the frequency and type of wind damage in the Hyrcanian forest in Iran. To do this, all the damaged trees were examined on both uphill and downhill sides of roads and the type of the damage (broken or windthrown), the horizontal distance between trees and road, diameter at breast height (DBH), tree species (mostly Oriental beech *Fagus orientalis* and European Hornbeam *Carpinus betulus*), height of breakage and slope of terrain were recorded for each damaged tree. We used a chi-square test of goodness-of-fit to assess the effect of road, DBH and slope on the frequency of damaged tress and logistic regressions to model the effects of different factors on the type of wind disturbance. Our results suggest that the frequency of damaged trees redu-

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ced with increasing distance from the road, i.e. frequency of damaged trees in 0-25 m distance class was about 7.4 times of that in 75-100 m. The frequency of damaged trees increased also with increasing slope and DBH and the highest number of damaged trees were observed in DBH class of 67.5-87.5 cm. Beech trees were mostly broken (87 %), while hornbeam trees showed higher percentage of windthrow (58 %) compared to beech trees. The results of logistic regressions indicated that one-unit increase in the distance from the road leads to 0.74 % increase in the probability of windthrow for both species. Surprisingly the probability of windthrow for hornbeam is about 4.3 times higher compared to beech at the same distance. In contrast the probability of wind breakage decreased with increasing distance from the road for both species and beech were more frequently broken than hornbeam. Climate change is expected to intensify natural disturbances and thus risk analysis of wind disturbance require increased attention in road planning and maintenance operations to reduce costs and increase safety in the future.

Zusammenfassung

Starke Winde sind eine wichtige natürliche Störung in temperierten-gemäßigten Wäldern, die Schäden, Bodenlücken, Störungen des Bodens und Änderungen in Vegetationszusammensetzung verursachen. Ziel dieser Studie war es, die Auswirkungen von Forststraßen als von Menschen gemachte Infrastruktur auf die Häufigkeit und Art von Windschäden im Hyrkanischen Wald im Iran zu untersuchen. Zu diesem Zweck wurden alle beschädigten Bäume bergauf- und bergabseitig von Forststraßen untersucht und die Art des Schadens (Bruch oder Windwurf), der horizontale Abstand von Baum zu Straße, der Brusthöhendurchmesser (BHD), die Baumart (überwiegend Orientbuche *Fagus orientalis* and Hainbuche *Carpinus betulus*), die Bruchhöhe und die Geländeneigung für jeden beschädigten Baum aufgezeichnet. Wir verwendeten einen Chi-Quadrat-Test der Passgenauigkeit, um die Auswirkung von Straße, Brusthöhen- und Neigungsdurchmesser auf die Häufigkeit der beschädigten Locken zu bewerten und eine logistische Regression, um die Auswirkungen verschiedener Faktoren auf die Art der Windstörung zu modellieren. Unsere Ergebnisse zeigten, dass die Häufigkeit von beschädigten Bäumen mit zunehmenden Abstand zur Straße sich verringert, d. h. die Häufigkeit von beschädigten Bäumen in 0-25 m Entfernung betrug etwa das 7,4-fache der Häufigkeit in 75-100 m. Die Häufigkeit geschädigter Bäume nahm auch mit zunehmender Hangneigung und BHD zu und die höchste Anzahl geschädigter Bäume wurde in der BHD-Klasse 67,5-87,5 cm beobachtet. Buchen sind überwiegend gebrochen (87 %), während Hainbuchen einen höheren Anteil an Windwürfen aufwiesen (58 %) als Buchen. Die Ergebnisse der logistischen Regression zeigten, dass eine Erhöhung Entfernung von der Straße um eine Einheit zu einer um 0,74 % höheren Wahrscheinlichkeit für Windwurf für beide Arten führt. Die Wahrscheinlichkeit für Windwurf einer Hainbuche ist jedoch etwa 4,3-mal höher als für eine Buche bei gleicher Entfernung. Im Gegensatz dazu nahm die Wahrscheinlichkeit eines Windbruchs bei beiden Arten mit zunehmendem Abstand zur Straße ab und Buchen wurden häufiger gebrochen als Hainbuchen. Klimawandel wird vermutlich

zu einer Intensivierung von natürlichen Störungen führen und daher bedarf es mehr Aufmerksamkeit für die Risikoanalyse von Windstörungen bei der Planung und Instandhaltung von Straßen hinsichtlich zukünftiger Kosten und Sicherheit.

Introduction

Forest disturbances can be classified into physical and biological disturbances (Fischer et al., 2013). Strong winds, snow breakage, snow avalanches, or fire are classified as physical disturbances, while biological disturbances may involve animal activities such as insect outbreaks, soil excavation (e.g. by wild boar), browsing (e.g. by deer, cattle or sheep) and mortality of trees caused by fungal diseases (e.g. oak dieback). Disturbances by humans, a rather new disturbance category, include both physical (e.g. felling of trees including clear-cutting, thinning and timber extraction, land use changing) and biological elements such as species selection and introducing of new species to the area (Fischer et al., 2013).

Damage to forest stands such as broken or windthrown trees due to high wind load (Sagi et al., 2019) are important physical natural disturbances affecting forests and may lead to serious disturbances to the ecosystem (Mitchell 2013; Magnabosco Marra et al., 2018; Dupont et al., 2018). Wind disturbance may lead to serious loss of economic value (Hanewinkel et al., 2013; Mitchell, 2013; Dupont et al., 2018), but also may simultaneously facilitate biodiversity (Thom and Seidl, 2016). Natural disturbances are key processes in all forest ecosystems influencing stand composition, biodiversity and trees physiology (e.g. transpiration) as well as their physical behavior (Zhu et al., 2004; Fischer et al., 2013). Strong winds are among the most important disturbances in temperate forests causing gaps of varying sizes, which ultimately can cause soil disturbance, changes in microclimate and induce changes in vegetation communities (Ulanova, 2000). Wind disturbance on the other hand also can lead to establishment of regeneration and consequently changes in forest structure (Samonil et al., 2009, Thom and Seidl, 2016). Strong winds can blow down (i.e. windthrow) single trees, small groups of trees or in severe cases very large areas or entire catchments. Tree susceptibility to wind depend on various parameters such as wind condition, terrain, and tree dimensions (Gardiner, 1995; Schindler et al., 2010, 2013; Angelou et al., 2019). Non stand-replacing disturbances are one of the main natural processes creating an uneven-aged forest structure (Lorimer, 1989), and are important agents of gap expansion (Worrall et al. 2005). While various factors including root rot or diseases may lead to wind damage of trees, the wind appears to be the most important factor (Peterson, 2007).

The probability of wind damage is driven by the resistance/robustness of trees and forest stands against the wind and the frequency of strong winds (Bouchard et al., 2009). Factors influencing the robustness of a stand include individual characteristics of trees, stand, soil, topography, and climate conditions (Stathers et al., 1994). Factors influencing the robustness of single trees include root system, angle of the main branches of the stem, form factor, canopy density, stem health, canopy weight and exposure to wind (Baradaran Motie and Shakeri, 2012). Important characteristics of trees root system are root depth, root density and roots distribution (Abdi and Deljouei, 2019). The resistance to wind disturbances differs between tree species (Zhu et al., 2006). Abdi et al. (2011) concluded that among three main species of the Hyrcanian forest including hornbeam (*Carpinus betulus*), oriental beech (*Fagus orientalis*), and Persian ironwood (*Parrotia persica*), the density of hornbeam roots was the lowest among three species. Furthermore, Bagheri (2012) reported a significant relationship between the frequency of wind damage and tree species, where hornbeam was reported to be more sensitive compared with oriental beech and Persian ironwood due to the superficial root system of hornbeam.

Damage due to severe winds in boreal, temperate, and mountainous forests did attract the interest of numerous researchers in recent years (Zhu et al., 2006; Fischer et al., 2013; Mitchell, 2013). Many studies have been conducted in the temperate zone of Europe (Brunner, 2002, Fischer et al., 2013, Schonenberger et al., 2002) and in the boreal zone of Russia (Lassig and Mocalov, 2000; Ulanova, 2000). Windstorms in a mixed conifer and broadleaved forest showed that thrown of trees in forest ecosystem created microsites with different soil characteristics and ultimately different vegetation communities (Phillips et al. 2008). Strong winds may also increase the speed of the succession by preferential felling of early-successional tree species in Minnesota (Dyer and Baird, 1997). Samonil et al. (2009) revealed that the wind damage events caused significant changes in species composition of mixed forest of oriental beech in the Carpathian Mountains.

To increase robustness versus winds, trees activate mechanisms, which result in increasing cambium divisional activity on the leeward, and secondary growth may stop completely on the windward of the trunk, causing oval shape of the stem. Moreover, the root system tends to form more roots on the dominant leeward (Nicoll and Ray, 1996). In addition, high road density, high trenches and excavations may cause damage to the root systems of trees, and trees located in the roadside are more susceptible to wind damage (Deljouei et al., 2017a). Limited root development of trees growing on shallow or saturated soil may also increase the probability of wind damage. In the case of heavy rains before the strong winds, trees are more likely to be thrown, whereas in dry soils, the trunk will be more likely to break. In older trees with root diseases and stem decay, the potential of stem breakage near the ground surface is higher. Some studies indicated that thrown is more prevalent in comparison to the two types of breakage from the upper and lower parts of the trunk (Bagheri, 2012). Moreover, the trees broken at a height of above two meters had significantly higher diameters than windthrown trees (Bagheri, 2012).

Forest road construction is an intense interference in the forest, which influences the microclimate in the stand (Formann et al., 2003; Perz et al., 2007). So far, numerous studies have investigated the impact of forest roads on the composition and diversity of plant species, soil condition, and the activity of the soil micro-organisms of adjacent stands (e.g., Deljouei et al., 2017b, 2018). However, no study has been carried out on the potential effect of roads on wind damage in forests. The main aim of this study was to assess the effect of road on the frequency and type of wind damaged trees in a part of the Hyrcanian forest in northern Iran. We also wanted to assess whether the probability of the type of wind disturbance (i.e. broken or windthrown) is associated with variables related to tree species, distance from the road, site slope, diameter at breast height (DBH) of the damaged trees and the position of the trees in relation to the road (upside or downside of the road).

Materials and methods

Study site

The study was conducted in the second district (called 'Namkhane') of the educational and experimental forest of the University of Tehran (Kheirud Forest), in the central part of the Hyrcanian forest in northern Iran. The district, covers an area of about 1083 ha *Fageto-Carpinetum* forest type, with 53.68 % beech, 35.03 % hornbeam and 11.29 % other species (including *Acer cappadocicum*, *Alnus subcordata*, *Diyospyrus lotus*, *Fraxinus excelsior*, *Parrotia persica*, *Tilia begonifolia* and *Ulmus glabra*). The mean number of stems per hectare, basal area and standing volume per hectare in the road adjacent compartments are 212, 29.38 m^2ha^{-1} and 443 m^3ha^{-1} respectively. The composition of species includes *Fagus orientalis* (53.68 %), *Carpinus betulus* (35.03 %), *Acer velutinum* (4.65 %), *Quercus castaneifolia* (1.02 %) and other species 5.62 %. The percentage of volume among species is as follow: *Fagus orientalis* (58.98 %), *Carpinus betulus* (25.85 %), *Acer velutinum* (6.63 %), *Quercus castaneifolia* (3.25 %) and other species 5.29 %. Elevation ranges from 350 to 1350 m above sea level, while the slope ranges from 0 to 80 degrees. The parent rock is composed of hard calcareous layers with a large number of cracks and the soil is generally Alfisol according to USDA soil taxonomy (Forest management plan, 2015). Average annual precipitation at the site is about 1081 mm, with average summer and winter temperatures of 22.5 °C and 10 °C, respectively. The current silvicultural system is the "selection system", which is considered to ensure sustainable management and yields. The future of the forest highly depends on natural regeneration in gaps. The road network of the district is consisting of main and secondary forest roads that were constructed in 1989 and therefore are 30 years old (Figure 1). The current research was conducted considering main roads with 5.5 m width, gravel surfacing and longitudinal gradient of 3-8 %. The total length of the forest road network in the district is 15.8 km. A segment with 5700 m length of main road was selected for the current study.

Figure 1: A typical part of the road network (left). Sometimes wind damaged trees can cause problem for traffic and safety (right).

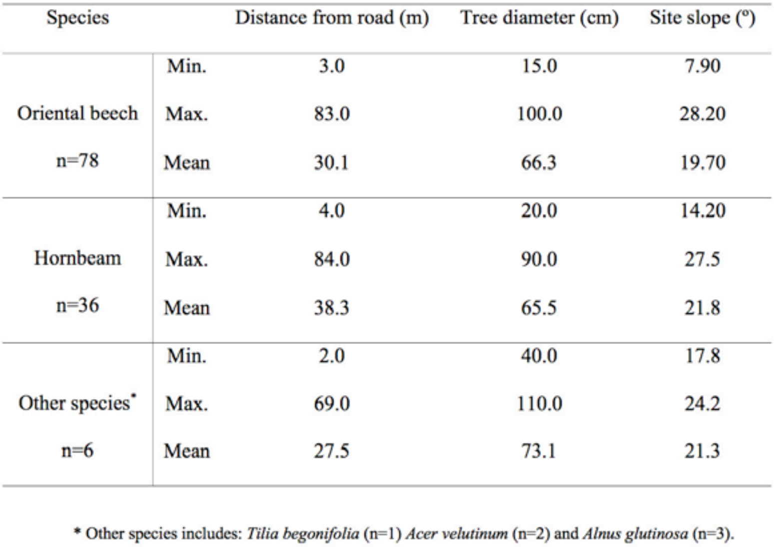
Abbildung 1: Ein typischer Teil des Straßennetzes (links). Manchmal verursachen Windwurfbäume Verkehrs- und Sicherheitsprobleme (rechts).

Data collection

A road segment with 5700 m length was selected from the main forest road network of the study area and all wind damaged trees at both sides of the road (i.e. up and downhill sides) were recorded in a buffer of 100 meters. The wind damaged trees were fallen over years and were not related to a one wind event. The age of storm events is estimated to be up to 10 years. Some descriptive statistics of 120 sampled trees are presented in table 1.

Table 1: Descriptive statistics of wind damaged trees (n=120).

Tabelle 1: Beschreibende Statistik von vom Wind geworfenen Bäumen (n = 120).



Species		Distance from road (m)	Tree diameter (cm)	Site slope (º)
Oriental beech n=78	Min.	3.0	15.0	7.90
	Max.	83.0	100.0	28.20
	Mean	30.1	66.3	19.70
Hornbeam n=36	Min.	4.0	20.0	14.20
	Max.	84.0	90.0	27.5
	Mean	38.3	65.5	21.8
Other species* n=6	Min.	2.0	40.0	17.8
	Max.	69.0	110.0	24.2
	Mean	27.5	73.1	21.3

* Other species includes: *Tilia begonifolia* (n=1) *Acer velutinum* (n=2) and *Alnus glutinosa* (n=3).

As the selected length of the road was 5700 m, an area of about 114 ha was surveyed (Figure 2). Parameters such as the distance of stumps from the road, diameter at breast height, tree species, wind damaged type (windthrown or broken), breaking height, site slope, visual qualitative examination and stumps coordination (in UTM system) of the damaged trees were collected. Damaged trees were usually among the largest stand trees.

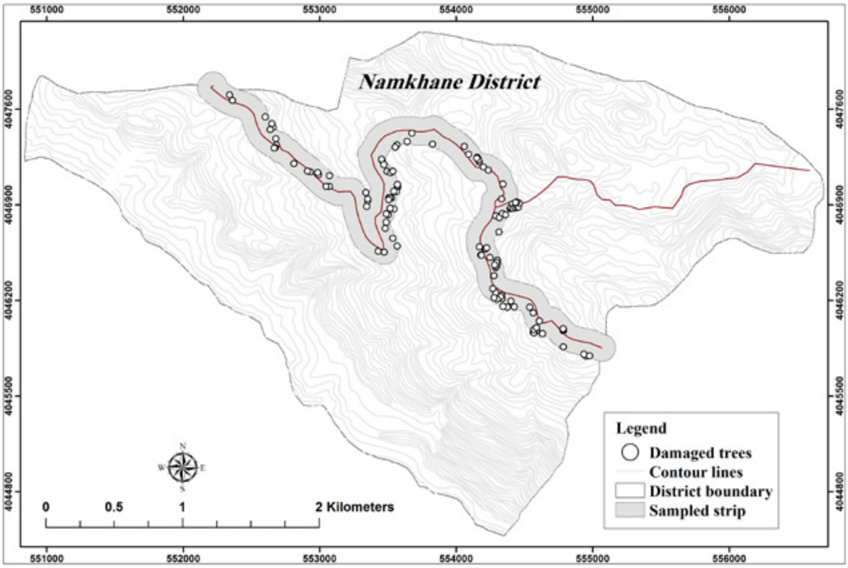


Figure 2: Study area, road network and samples.

Abbildung 2: Untersuchungsgebiet, Straßennetz und Stichproben.

Analyses

The observed data for distance from the road, diameter at breast height and site slope were transformed from continuous observations into categories. Distance from the road was grouped into four categories defined as 0-25, 25-50, 50-75, and 75-100 m; the diameter at breast height was classified to five categories defined by 12.5-27.5, 27.5-47.5, 47.5-67.5, 67.5-87.5, and 87.5- 107.5 cm and site slope was classified into two categories as: 0-15 % and 15-30 %. A chi-square test of goodness-of-fit was performed to determine whether the frequency of wind damaged trees were equally distributed in the different categories of distances and site slope.

Logistic regression was used to assess the effects of different factors on the type of wind damaged trees (windthrown or broken). Using the subset of dataset with beech and hornbeam as the most frequent samples, which contains 114 observations (95 % of total disturbed trees), we modeled wind disturbance type as a function of five predictors as follows (Hosmer et al., 2013).

$$Logit(p) = Log\left(\frac{p}{1-p}\right) = \alpha + \sum_{i=1}^{k} \beta_i x_i \qquad (1)$$

where p is the probability that damage will occur, 1-p is the probability that it will not occur, α is the intercept, β refers to the coefficients and x represents the independent variables (distance from the road, diameter at breast height and site slope). It was usually concerned with the predicted probability of an event occurring and that is defined by:

$$p = \frac{1}{1+\exp(-z)} \tag{2}$$

$$\text{where } z = \alpha + \sum_{i=1}^{k} \beta_i x_i \,.$$

Considering the unbalanced dependent variable, the method suggested by King and Zeng (2001, 2004) was used to get better parameter estimates. The variables collinearity was investigated using variance inflation factor (VIF) and only variables with VIF less than 5 were included in the model. A Wald test was used to evaluate the statistical significance of each coefficient in the model. Testing the null hypothesis that the set of coefficients is simultaneously zero for final model was implemented using likelihood ratio test. There are several ways to assess the predictive ability of each model. While no exact equivalent to the R-square of linear regression exists, Mc Fadden Pseudo R-squared was used to assess the model fit (McFadden, 1974, 1977). The measure ranges from 0 to 1, with values closer to zero indicating that the model has no predictive power and the measure between 0.2 and 0.4 are considered to indicative of good model fits (Louviere et al., 2000). Classification tables (also called a confusion matrix) can also be used to assess the number of correct prediction within each response class at a chosen cut off probability. The optimal cutoff was calculated to minimize the misclassification error for the model. The model prediction accuracy indices including classification accuracy, classification specify and classification sensitivity were calculated based on classification table.

A Receiver Operating Characteristic Curve (ROC) is another measure of model performance (Agresti, 2002, Metz, 1978). The Area under the Curve (AUC), is an accepted traditional performance metric for a ROC curve. The measure ranges from 0.50 to 1.00. An area of 1 under the ROC curve represents a perfect model, while an area of 0.5 represents a worthless model.

When evaluating models, it is common to assess the model performance using completely new/independent set of observations that have not been used in model fitting. When not having an independent dataset, a method for the evaluation, is to perform a leave-one-out cross-validation. By using this technique, one observation is held out for testing the model while the others are used to fit the model and then the model is used to predict the target variable for that observation. This process is repeated to the number of observation times, and the performance of the model in predicting the left out set being evaluated using performance metrics.

Results

Total number of wind damaged trees in different distance classes from the road are presented in Figure 3. The results revealed that the number of wind damaged trees decreased with increasing the distance from the road, and damaged trees in 0-25 m was about 7.4 times higher than 75-100 m distance class. R-squared of fitted model (0.97) showed that a high proportion of variation in the frequency of wind damaged trees in each distance class is justified by this model where the x is midpoint of each distance class.

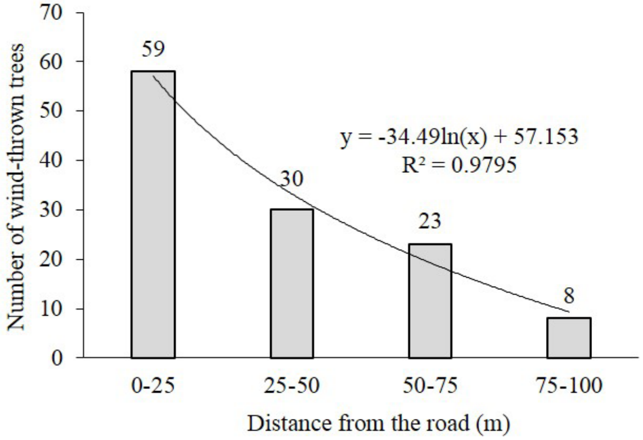


Figure 3: Frequency of the wind damaged trees at different distance classes from the road.

Abbildung 3: Häufigkeit der vom Wind geworfenen Bäume in verschiedenen Entfernungsklassen von der Straße.

The relationship between the frequency of the wind damaged trees and diameter classes revealed that generally wind damaged trees frequency increased by increasing tree diameter, and the only exception is diameter class of 87.5-107.5 cm (Figure 4). The highest frequency belongs to 67.5-87.5 cm DBH class with 45 samples in this class.

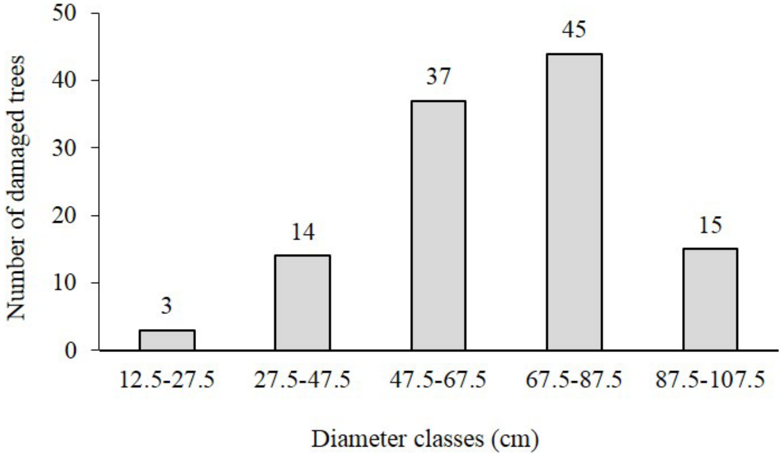


Figure 4: Frequency of wind damaged trees at different diameter at breast height classes.

Abbildung 4: Häufigkeit windgeworfener Bäume mit unterschiedlichem Durchmesser in Brusthöhenklassen.

The frequency of wind damaged trees at two slope classes (0-15° and 15-30°) shows that the number of damaged trees were higher in 15-30° slope class with 98 observations versus 16 observations for 0-15°. A chi-square test of goodness-of-fit was performed to determine whether the frequency of wind damaged trees were equally distributed in the two categories of slope classes. The result indicated that wind damaged trees were not equally distributed within the slope classes, ($X^2 = 60.965$, df = 1, $p < 0.01$).

The percentage of damaged trees regarding tree species showed that the highest damage category for oriental beech was broken trees (87 %) while for hornbeam, windthrown observations were higher (58 %),

Assessing the breaking height of the wind damaged trees demonstrated that the majority of the trees were broken at less than 3 m height in all distance classes (Figure 5).

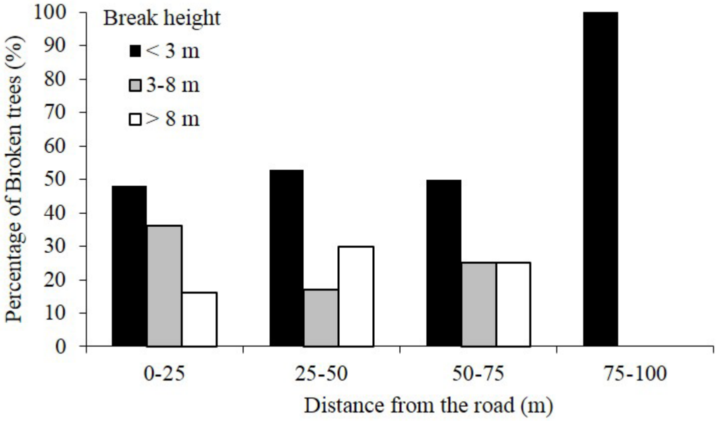


Figure 5: Percentage of breakage height of the broken trees at different distances from the road.

Abbildung 5: Prozentsatz der Bruchhöhe der vom Wind geworfenen Bäume in unterschiedlichen Abständen von der Straße.

The percentage of total wind damaged trees regarding the type of damage (windthrown or broken) in different distances from the road showed that the number of broken trees decreased with increasing distance from the road, however, we found the opposite for windthrown trees (Figure 6).

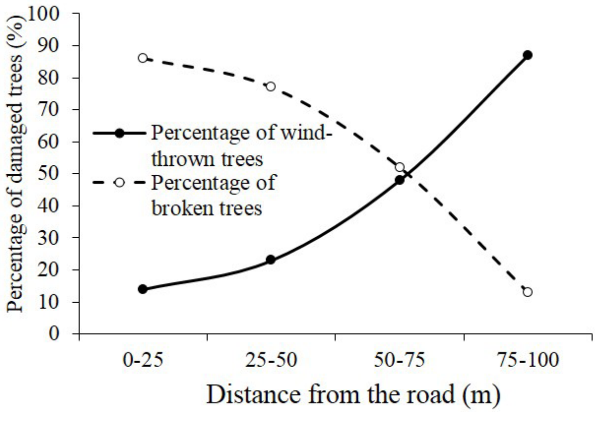


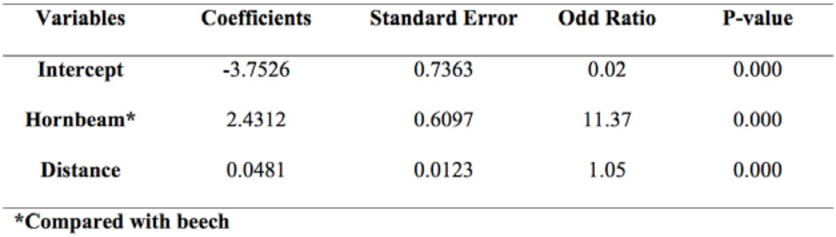
Figure 6: Percentage of windthrown and broken trees at different distances from the road.

Abbildung 6: Prozentsatz der entwurzelten und abgebrochenen Bäume in unterschiedlichem Abstand von der Straße.

The parameter estimates, odd ratios and statistical significance of final logistic regression coefficients are presented in Table 2. Non-significant variables such as the position of the trees in relation to the road were excluded from the model in the process of model development in a backwards elimination. According to the Table 1, both distance and species explain a significant amount of variation in the probability of wind damage type ($p < 0.05$).

Table 2: Parameter estimates odd ratios and statistical significance of regression coefficients.

Tabelle 2: Parameterschätzungen für ungerade Verhältnisse und statistische Signifikanz von Regressionskoeffizienten.



Variables	**Coefficients**	**Standard Error**	**Odd Ratio**	**P-value**
Intercept	-3.7526	0.7363	0.02	0.000
Hornbeam*	2.4312	0.6097	11.37	0.000
Distance	0.0481	0.0123	1.05	0.000

***Compared with beech**

The regression equation is:

$$Log\left(\frac{p}{1-p}\right) = -3.7525 + 2.4312(carp) + 0.0481(dist) \tag{3}$$

It is estimated that for every one-unit increase in the distance, the odds of having windthrown trees increases by 1.05. The odds-ratio of windthrown for hornbeam compared to beech of the same distance is 11.37. Thus the odds of windthrown is about 11.37 times greater for hornbeam than beech of the same distance. To simplify this, we assumed that the rate of probability changes for an event is constant across the range of distances. Based on this assumption, one-unit increase in the distance from the road leads to 0.74 percent increase in the probability of being wind thrown for both species. However, probability of being wind thrown for hornbeam trees is about 4.3 times of that for beech trees at the same distance. In contrast, beech showed more broken trees than hornbeam and the probability of wind breakage decreased with increasing distance from the road for both species (Figure 7).

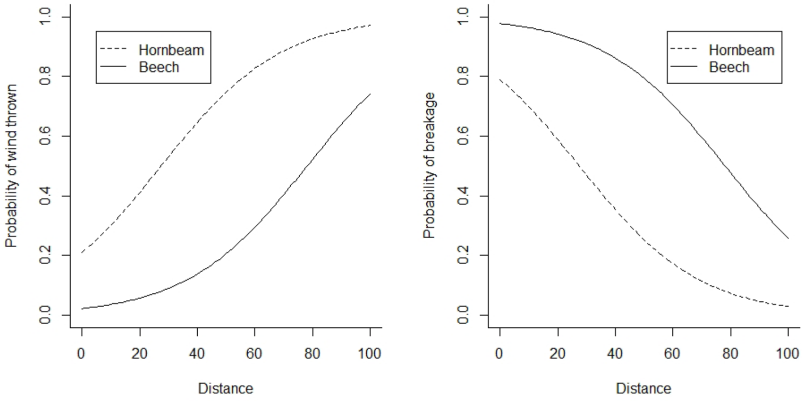


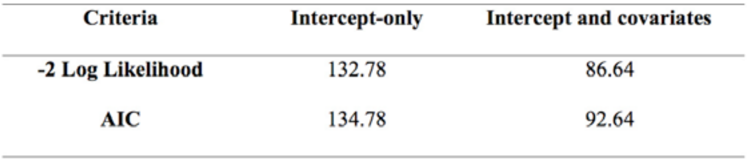
Figure 7: Predicted probability based on logistic regression.

Abbildung 7: Prognostizierte Wahrscheinlichkeit basierend auf logistischer Regression.

The chi-square statistic shows significant difference between the null deviance and the residual deviance of the model ($p < 0.05$). This indicates that the model gives a significant improvement over the baseline intercept-only model (Table 3).

Table 3: Model fit statistics from logistic regression model.

Tabelle 3: Modellanpassungsstatistik aus dem logistischen Regressionsmodell.

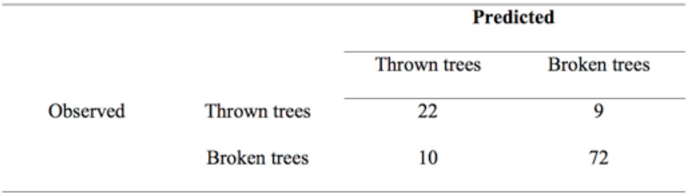


Criteria	Intercept-only	Intercept and covariates
-2 Log Likelihood	132.78	86.64
AIC	134.78	92.64

Mc Fadden Pseudo R-squared was 0.31 that is an indicative of good model fit. The optimal cutoff to minimize the misclassification error was 0.35. Classification table was constructed based on predicted values from leave-one out cross validation (Table 4). The model performance metrics are presented in Table 5. The final model accurately predicted 83 % of observation using leave-one out cross validation, which is a satisfying performance. The area under the ROC curve (0.85) is also an acceptable result.

Table 4: Classification table based on leave-one-out cross validation.

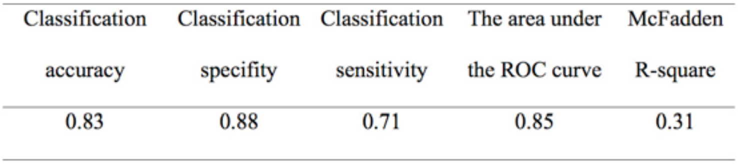
Tabelle 4: Klassifizierungstabelle basierend auf einer einmaligen Kreuzvalidierung.



		Predicted	
		Thrown trees	Broken trees
Observed	Thrown trees	22	9
	Broken trees	10	72

Table 5: Model performance based on leave-one-out cross validation.

Tabelle 5: Modellleistung basierend auf einer einmaligen Kreuzvalidierung.



Classification accuracy	Classification specifity	Classification sensitivity	The area under the ROC curve	McFadden R-square
0.83	0.88	0.71	0.85	0.31

Discussion

The findings of this study revealed that with increasing distance from the road, the number of the wind damaged trees decreased, so that the number of the wind damaged trees in the distance of 0-25 m was three times higher than other distances. As these forests are managed, it is also possible that the higher windthrow probability is an effect of more intense management closer to the forest road. Whenever, the wind enters to the open corridors (such as road corridor), it moves rotationally and causes more damage (Bagheri, 2012). In agreement to our findings, Stathers et al. (1994) demonstrated that wind damage usually occurs on the downwind edge of cutblocks/cut areas and can extend into the stand for 100 m, although most damage was usually concentrated within the first 10-20 m of the boundary of the cut area. However, the power and speed of the wind reduces with increasing distance from the road/cut area. Canopy density and its area against wind are among the most important factors in the wind damage of trees (Baradaran Motie and Shakeri, 2012), so the trees closer to the road are more likely to be damaged due to their larger canopy area compared to the trees at further distances from the road. In this regard, the damaged trees were extracted from forest for providing rural fuelwood after the first inventory phase and unfortunately we could not conduct the canopy measurements.

Generally, the diameter distribution in uneven age forests such as the study area has a negative exponential trend, resulting in a low number of large trees (Forest management plan, 2015). An examination of the wind damaged trees in terms of diameter classes showed that, with increasing diameter, the percentage of the wind damaged trees increased, however, this trend is not observed in the diameter class of 87.5-107.5 cm. The qualitative examination of wind damaged trees revealed that the hollowness of the trees in the study area have exacerbated the wind damaged events. Therefore, trees with diameter classes of 60 cm or higher were more likely to break due to increased hollow volume. The low number of the wind damaged trees in the diameter classes over 90 cm observed in this study was logical, considering the diameter distribution curve, which has a decreasing trend, resulting in trees over 90 cm DBH being rare trees compared to smaller ones. Trees with lower diameters, albeit their larger number in uneven age natural stands, were less likely to break due to higher elasticity, being healthy and lack of hollowness in the stem. Scott and Mitchell (2005) also found that tree DBH was positively correlated with probability of wind damage. Also, Peterson (2004) predicted the wind damage status of 90 % of trees within five stands in USA damaged by severe thunderstorms using only tree species and DBH.

Topographic factors significantly affect the overall pattern of tree damage by wind, as the wind damage increases with increasing slope gradient (Zhu et al., 2006). In the inclined surfaces, the tree's resistance to stress is less, and in case the wind is in the same direction of the hillside, the severity of damage is higher. In this study, the number of the wind damaged trees increases with increasing slope gradient. However, the results of logistic regression analysis revealed that the slope did not have a significant effect on the type of the wind damage. Nevertheless, the results may be affected by the limited range of the slope variation in the studied area adjacent to the road.

According to the logistics model, the probability of broken trees decreases with increasing distance from the road for both hornbeam and beech trees. A tree trunk may break when the root resistance is higher than the trunk resistance to the wind. Decay or hollow part in the trunk is the most important factor influencing on trunk resistance. If the diameter of the hollow part of the tree trunk exceeded 40 % of the total stem diameter, the rate of breaking of the trees would increase suddenly (Baradaran Motie and Shakeri, 2012). Half of the broken trees in the first three distance classes were broken at a height of less than 3 m, indicating that these trees were hollow in the lower section and they could not withstand the wind. Higher number of the trees with hollowness problem near the road could be due to damage to these trees during road construction and skidding or stone-to-tree stem collisions or the burial of the tree collars in the road's embankment. Old trees with root diseases and stem decay increase the possibility of the trunk breakage near the surface of the ground (Bagheri, 2012).

In contrast to the breakage damage, the percentage and probability of windthrown get larger with increasing the distance of trees from the road for both hornbeam and beech trees. The inverse relationship between the ratio of broken and windthrown trees with the distance from the road can be probably attributed to the fact that trees far from the road have less damage and decay problems in their trunk and as a result that their trunk have more resistance against the breakage (Mitchell, 2013), however, strong winds can throw them. Furthermore, trees closer to the road usually have more access to the light and probably allocate more biomass for their root systems than the trees inside the stand (Bagheri, 2012).

Based on explorative analyses, for the oriental beech, most of the wind damaged trees were broken and least of them were thrown. However, for hornbeam, the rate of windthrown trees was greater than that of broken ones. These results are in line with the results of the study by Bagheri (2012). Comparison of the type of wind damage between oriental beech and hornbeam based on logistic regression also indicated that, the probability of windthrown for hornbeam was higher than that for beech trees at the same distance. In contrast, beech trees exhibited more broken trees compared to hornbeam at the same distance. Broken or windthrown damage among different species depends on the threshold of resistance of the trees and stand against wind (Bouchard et al., 2009), individual characteristics of trees, mass, soil, topography, and climatic conditions (Stathers et al., 1994). The oriental beech species has a more developed root system compared with hornbeam, however, its stem is usually decayed and hollow, with a physical structure that is broken more easily (Mitchell, 2013). Therefore, the higher rate of windthrown in hornbeam species compared to oriental beech could be due to the fact that this species has a superficial root system (Bagheri, 2012) and roots with lower diameter and lower resistance compared with oriental beech (Abdi et al., 2011). The most important parameters affecting root system are rooting depth, root diameter and distribution of roots with the highest effect on the resistance of trees against wind. Regarding the implications, considering the expected effect of climate change in intensifying natural disturbances (Haughian et al. 2012; Seidl et al. 2017), risk analysis of wind disturbance requires increased attention in road planning and maintenance operations in terms of costs and safety in the future. Generally, as disturbances cannot be prevented, any treatment (e.g. modifying the height, spacing or species of edge trees) that avoid abrupt forest edges is likely to be beneficial (Gardiner and Stacey, 1996). As Gardiner and Stacey (1996) showed, even a narrow modified strip around the forest edge can be effective in reducing the risk of wind damage. Wind damage may be reduced through a framework of general risk management through identifying spatially susceptible areas for wind disturbance (Mitchell, 2013) and also protection of edges like forest roads may be achieved by planting tapered or graduated density edges. Also the main wind direction could be considered when building future new forest roads.

Conclusion

We assessed the effect of forest roads on the frequency and type of wind damaged events in a part of the Hyrcanian forest. The results revealed that the frequency of wind damaged trees were reduced by increasing the distance from the road, although their frequency were increased with increasing site slope and stem diameter. Also the results indicated that the probability of thrown trees increases with increasing distance from the road for both hornbeam and beech trees. However, the probability of thrown for hornbeam was higher than that for beech at the same distance. In contrast, beech trees showed more breakage than hornbeam and the probability of wind breakage decreased with increasing distance from the road for both species. Further studies on the effect of road on wind damaged trees should consider additional factors such as canopy density and area and height/diameter coefficient that might influence the frequency of damage.

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