



RESEARCH ARTICLE

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# Risk model of tree stand damage by winds and its evaluation based on damage caused by cyclone “Xaver”

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## Abstract

*Aim of study:* To develop and evaluate the forest’s wind-risk model, dedicated for stand damage level.

*Area of study:* Model was tested in the northeastern Poland.

*Material and methods:* A risk model referring to the damage of forest stands by wind specifies, for every stand in a selected forest district, the risk factor within the range of 0 to 3. The higher value of the factor, the greater risk of damage, if wind occurs. The model was based on 11 features: average size of a tree stand, mean diameter breast high in the specified features’ ratio, species composition, degree of stand density, age of stand, forest site type, amount of damage caused by wind in the last 10-year period, location of forest district in the region of Poland, and three features for mountains: stand’s altitude above sea level, direction, and slope. The model used information from the State Forests’ Information System database (SILP), and since it was developed in JAVA computer language, the processing of data for one forest district lasted less than one minute.

*Main results:* The model can create a forest district digital map, in which stands characterized by specific risk values are presented with high prediction accuracy.

*Research highlights:* The risk model of tree stand damage by winds uses data provided by the SILP and what was proven in below study, can be used as an effective tool in a forestry practice.

**Additional keywords:** wind; damages; modeling; forests.

**Authors’ contributions:** Conceived, designed and performed the experiments; analyzed the data: AB, ED. Contributed reagents/materials/analysis tools; wrote the paper AB, ED, RB. Administrative and technical support: RB. All authors read and approved the final manuscript.

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## Introduction

In the current 21<sup>st</sup> century, many extreme weather events have been noted, which resulted in extensive damage throughout the forests of Poland. The most notable included hurricane winds, whirlwinds, wet snowfalls and freezing rainfalls, as well as droughts. From 2005 to 2014, the level of damage in forests, measured by the volume of acquired raw material after disasters, exceeded 36 million m<sup>3</sup>. Most damage to forests was caused by strong winds. Specifically, five hurricanes have hit Poland and left large-scale destruction.

In July 2002, northeastern Poland was affected by an intense squall with whirlwinds, heavily damaging the forests of Puszcza Piska, Puszcza Borecka, and Puszcza Kurpiowska with tree stands in Pisz and Drygały forest districts suffering most (Mikułowski, 2002;

Filipek, 2008). In November 2004, Hurricane “Pio” damaged the tree stands of the Regional Directorates of State Forests in Katowice and Kraków. Estimated by the volume of broken, fallen, and snagged trees, the damage was approximately 2 million m<sup>3</sup>. Substantial damage was caused in the forests of Beskid Śląski i Żywiecki, accelerating the degradation of spruce stands in Western Beskidy (Szabla, 2009; Bruchwald & Dmyterko, 2010). The year 2007 was characterized by extensive damage to forests, caused by one of the greatest intercontinental hurricanes, “Kyrill.” Damage mostly occurred in the southwest to tree stands in the Regional Directorates of State Forests in Wrocław, Katowice, and Kraków, as well as forest districts located in the south of Directorate in Zielona Góra and Poznań (Filipek, 2008; Grabowski, 2008). In 2009, severe damage was caused by a hurricane to the forests of the Directorate of State Forests in Wrocław and

Poznań. December 2013 was disastrous for forests when Cyclone “Xaver” caused severe damage in the tree stands of northwestern Poland, in the Regional Directorates of State Forests in Szczecinek.

The Forest Research Institute (Raszyn, Poland) has been conducting research on the impact of winds on forests since the 1990s (Zajączkowski, 1991; Zajączkowski *et al.*, 2004; Zachara, 2006). The result of these investigations has been the development of a risk model of tree stand damage by winds and the basis for this development were damage events in forests caused by the first three of the aforementioned hurricanes (Bruchwald & Dmyterko, 2010, 2013).

The purpose of this paper was to present the risk model of tree stand damage by winds, for lowlands, as well as for mountain regions. The evaluation of the model will also be carried out based on new empirical material, not previously taken into account, related to damage to tree stands caused by Cyclone “Xaver.”

## Material and methods

### Risk model development

The risk model of tree stand damage by winds was developed in five phases, resulting in more detailed model variants. The execution of the first phase, based on five tree stand features, resulted in the development of the first variant of the model in the form of the following formula (Bruchwald & Dmyterko, 2010, 2011, 2012, 2013):

$$R_1 = 0.505 X_1 + 0.030 X_2 + 0.240 X_3 + 0.160 X_4 + 0.065 X_5 \quad [1]$$

where  $R_1$  is a dependent variable risk factor for tree stand damage, and may have a value from 0 to 3, which corresponds to the range from very low- to very high-risk. Independent variables are related to the following tree stand features:  $X_1$  = average height of the main tree species in a tree stand;  $X_2$  = age of the main species;  $X_3$  = species composition of a tree stand;  $X_4$  = slenderness of the main species; and  $X_5$  = stocking index, and for plantations and thickets, density.

The main species of a tree stand is characterized by the greatest share of area.

— $X_1$  (variable) is characterized by the following formula:

$$X_1 = \frac{H}{12} \quad [2]$$

where  $H$  is an average height of the main species in a tree stand.

If  $X_1 > 3$ , the following should be adopted:  $X_1 = 3$ .

— $X_2$  (variable) is characterized by the following formula:

$$X_2 = \frac{w}{40} \quad [3]$$

where  $w$  is an age of the main species.

If  $X_2 > 3$ , the following should be adopted:  $X_2 = 3$ .

— $X_3$  (feature) is related to the species composition of a tree stand and is characterized by the following formula:

$$X_3 = \frac{u_1 \cdot y_1 + u_2 \cdot y_2 + \dots + u_k \cdot y_k}{u_1 + u_2 + \dots + u_k} \cdot z \quad [4]$$

where  $u_1, u_2, \dots, u_k$  – are the proportions of individual tree species in a tree stand;  $y_1, y_2, \dots, y_k$  are risk factors for individual tree species, describing their susceptibility to wind damage;  $k$  is the number of tree species in a tree stand;  $z$  is a rate, which for tree stands with the main species ( $H$ ) > 10 m, adopts the value of 1, and when ( $H$ ) < 10 m, adopts the value of  $H/10$ .

Risk factors for a tree species are included within the range from 0 to 3 (Table 1). These factors show that the tree species most endangered by wind are spruce; the least are Rowan, pear, and apple.

— $X_4$  (variable) is obtained from the slenderness reversal expressed in percent value ( $S$ ):

$$S = 100 \frac{D}{H} \quad [5]$$

where  $D$  = average diameter at breast height (DBH) of the main species, and  $H$  = average height of the main species.

**Table 1.** Tree species damage risk coefficient.

		Risk coefficient				
0	0.5	1	1.5	2	2.5	3
Mountain ash	Hornbeam	Oak	Birch	Pine	Fir	Spruce
Willow	Alder	Red oak	Downy birch		Douglas fir	
Mountain pine	Gray alder	Beech	Aspen			
Apple tree	Acacia	Maple	Linden			
Pear	Swiss pine	Sycamore	Larch			
	Elm	Ash				
	Scots elm					

If:

$$S \leq 60, \text{ then } X_4=0 \quad [6a]$$

$$60 < S \leq 120, \text{ then } X_4 = \left( \frac{S}{20} - 3 \right) \cdot z \quad [6b]$$

$$S > 120, \text{ then } X_4 = 3 \cdot z \quad [6c]$$

where  $z$  is specified as in the formula [4].

— $X_5$  (variable) is related to the stocking index or density ( $Zad$ ), and calculated based on stated below equations:

If:

$$Zad \leq 0.6, \text{ then } X_5 = 5 \cdot Zad \cdot z \quad [7a]$$

$$0.6 < Zad \leq 1.0, \text{ then } X_5 = 5 \cdot (1,2 - Zad) \cdot z \quad [7b]$$

$$Zad > 1.0, \text{ then } X_5=z \quad [7c]$$

where  $z$  is specified as in the formula [4].

— $X_6$  (variable) is related to the forest type and calculated on the formula [8], using data from table 2.

Variant 2 of the risk model for tree stand damage by winds was developed from the first variant, taking into

**Table 2.** Forest type damage risk coefficient.

Forest type	Risk coefficient
Dry coniferous forest	0
Fresh coniferous forest	0.5
Fresh mixed coniferous forest	
Wet mixed coniferous forest	1
Fresh mixed deciduous forest	
Fresh deciduous forest	
Wet coniferous forest	1.5
Wet mixed coniferous forest	
Wet mixed deciduous forest	
Wet deciduous forest	
Upland's mixed coniferous forest	
Upland's mixed deciduous forest	
Riparian deciduous forest	2
Alder forest	
Alder-ash forest	
Swampy coniferous forest	
Swampy mixed coniferous forest	
Swampy mixed deciduous forest	
Upland's deciduous forest	
Mountain's deciduous forest	
Mountain's mixed deciduous forest	
Mountain's coniferous forest	
Mountain's mixed coniferous forest	
Mountain's wet coniferous forest	2.5
Mountain's wet deciduous forest	
Mountain's deciduous forest	
Mountain's swampy coniferous forest	3
Mountain's alder forest	
Mountain's riparian forest	
Mountain's alder-ash forest	

account a variable related to the forest habitat type ( $X_6$ ). This variable is specified by the following formula:

$$X_6 = \frac{z \cdot W_s}{12} \quad [8]$$

where  $W_s$  constitutes a risk factor related the forest habitat type (Table 2), and  $z$  is a rate defined in formula [4].

Variant 2 of the risk model has the following formula:

$$R_2 = R_1 + X_6 \left( 1 - \frac{R_1}{3} \right) \quad [9]$$

Individual regions of the country are characterized by different probabilities of wind damage occurrence in forests. The probability is described by a rate of the regional risk of tree stand damage by winds ( $W_{rru}$ ), specified for individual forest districts based on the volume of broken, fallen, and snagged trees acquired in the years 2004-2014. The greatest values of those rates are for forest districts of the Regional Directorates of State Forests in Wrocław and Katowice, as well as individual forest districts of Directorates in Gdańsk, Olsztyn, and Białystok (Fig. 1).

— $X_7$  (variable) is related to the location of forest district and calculated on the formula [10].

A variable related to the location of a tree stand in a country region is specified by the following formula:

$$X_7 = \frac{z \cdot W_{rru}}{10} \quad [10]$$

Variant 3 of the risk model of tree stand damage by winds was developed from variant 2, taking into account the  $X_7$  variable (Bruchwald & Dmyterko, 2011):

$$R_3 = R_2 + X_7 \left( 1 - \frac{R_2}{3} \right) \quad [11]$$

Variant 4 of the model takes into account the volume of broken, fallen, and snagged trees, which have arisen in a tree stand within the last 10-year period. The rate taking such damage into account ( $W_{sz}$ ) has the following form:

$$W_{sz} = \sum \frac{[10 - (rb - r_i)] \cdot V_i}{30 \cdot H} \quad i = 1, 2, \dots, 10 \quad [12a]$$

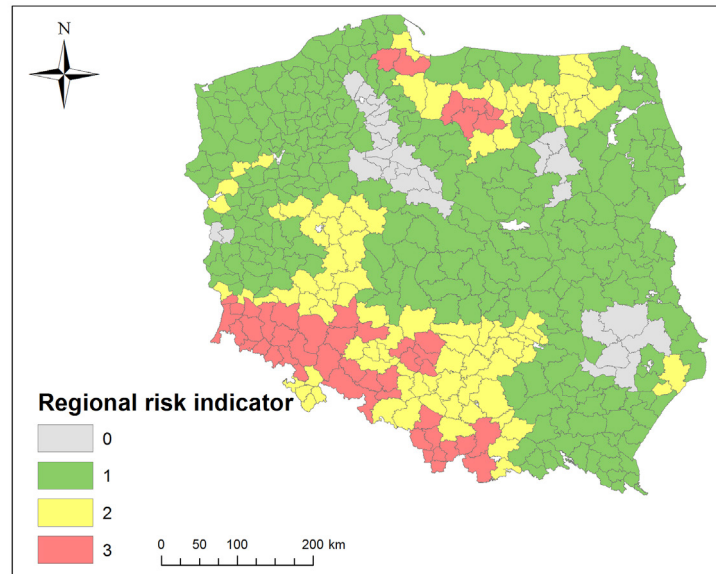
where  $rb$  = current year;  $r$  = year when the damage occurred;  $V$  = volume of trees damaged by winds or other factors converted to area in ha; and  $H$  = average height of the main species. Sigma refers to  $i = 10$  most recent years.

The  $W_{sz}$  rate has the following restrictions:

$$\text{If } W_{sz} > 1, \text{ then } W_{sz}=1 \quad [12b]$$

If winds damage the total tree stand, then  $W_{sz}=0$  [12c]

— $X_8$ . Based on the  $W_{sz}$  rate, the  $X_8$  feature is specified by the following formula:



**Figure 1.** Regional forest stand's wind damage risk coefficient.

$$X_8 = z \cdot W_{sz} \quad [13]$$

with the restriction that if  $X_8 > 1$ , it is necessary to adopt  $X_8 = 1$ .

Variant 4 of the risk model of tree stand damage by winds has the following form:

$$R_4 = R_3 + X_8 \quad [14]$$

restricted by the fact that if  $R_4 > 3$ , it is necessary to adopt  $R_4 = 3$ .

Variant 4 is a target risk model of tree stand damage by winds for forest districts located in lowland areas. For mountain areas, Variant 5 of the model has been developed, in which the following additional terrain features have been taken into account: tree stand aspect (Feature *A*), slope (Feature *B*), and of tree stand above sea level (Feature *C*).

The risk factor related to the tree stand damage resulting from terrain features *A*, *B*, and *C* is specified by the following formula:

$$X_9 = (0.2 \cdot A + 0.1 \cdot B + 0.7 \cdot C) \frac{h}{240} \quad [14a]$$

Variant 5 of the model adopts the following form:

$$R_5 = R_4 + X_9 \left(1 + \frac{R_4}{3}\right) \quad [15]$$

## Data sources

In the first decade of December 2013, Europe, including Great Britain, Holland, Belgium, Germany, Denmark, Sweden, and Poland, suffered from the powerful Cyclone “Xaver.” Maximum wind speed exceeded 200 km/h; the minimum air pressure fell

to 960 hPa. The storm was accompanied by snowfall and hail. The death toll was 15 people. By the time the cyclone reached Poland, it was weaker, with a maximum wind speed of 120 km/h.

The greatest wind damage to forests occurred in northwestern Poland. Therefore, forests of the Regional District of State Forests in Szczecinek were further analyzed. This Regional District includes 30 individual forest districts, where the primary tree type is the pine tree, having a 64.6% share in the area. Other species present are birch – 9.4%, beech – 9.2%, spruce – 6.0%, oak – 4.8%, alder 3.3%, larch – 1.6%, and remaining species – 0.9%. The dominating habitat types are fresh mixed coniferous forest (32.4%), fresh coniferous forest (23.9%), fresh mixed hardwood forest (19.7%), and fresh hardwood forest (12.1%).

Empirical data coming from the State Forests' Information System (SILP) database is related to the volume of every timber acquired from tree stands, along with its type classification, and its assignment to whether it is broken, fallen, or snagged. The consequences of Cyclone “Xaver,” which started in December 2013 and stretched into the year 2014, were analyzed in this study.

The SILP also provided taxation features for every tree stand in the forest district under Regional Directorate of State Forests in Szczecinek: area of a tree stand secretion (tree stand); stocking index or density level; type of forestry enterprise; forest habitat type; vertical structure; cutting age; species composition of a tree stand; and information for individual tree types such as their share of the area, age, average diameter at breast height (DBH), and average height.

Digital maps of the forest districts have also been used in this study.

Trees damaged by winds may be divided into the following categories: broken trees = trees that have been broken at a certain height of the trunk; fallen trees = uprooted trees; trees bent by the storm, which have not returned to their original, vertical position after the storm; trees cut down to form the border between a tree stand and gaps in the stand; and trees withered over a period of time, as a result of crown damage, trunk damage, or uprooting by winds.

The investigated tree damage categories may also arise for reasons other than high winds. Broken, fallen, and bent trees may equally be found after heavy snowfalls or tree icing. Snagged trees are formed as a result of the tree growing processes and competition, but drought or industrial emissions may also accelerate this process. Frequently, damaging factors occur simultaneously, making it difficult or impossible to identify a single cause of tree death.

A significant methodological problem is the definition of the terms damaged stand and undamaged stand. In this work, a damaged stand refers to a tree stand where the total volume of specified tree categories converted to the area of 1 ha, exceeds the critical value ( $V_k$ ), set by the following formula (Bruchwald & Dmyterko, 2010):

$$V_k = 1 + \frac{H}{12} \quad [15]$$

where  $H$  is the average height of the main tree stand species.

If the volume of the specified tree groups is higher than the critical value, the tree stand is considered damaged. Formula [15] refers to stands of all age classes, including plantations and thickets.

Having relevant data for a given forest district, Variant 4 of the risk model of tree stand damage by winds has been applied, *i.e.*, the variant appropriate for lowlands. For every tree stand, damage risk factors

( $W_r$ ) have values from 0 to 3. Based on these values, the rate empirical distribution was generated, adopting six classes, each 0.5 wide: Class 1:  $W_r \leq 0.5$ ; Class 2:  $0.5 < W_r \leq 1$ ; Class 3:  $1 < W_r \leq 1.5$ ; Class 4:  $1.5 < W_r \leq 2$ ; Class 5:  $2 < W_r \leq 2.5$ ; and Class 6:  $W_r > 2.5$ .

Tree stands classified as Class 1 are characterized by a very low risk of damage, and along with the growth of the class, the risk as follows: low, increased, moderate, high, and very high (Class 6).

Upon the classification of every tree stand into a risk factor class, the total area of tree stands in each class was determined. This area was then expressed as a percentage of the total forest area of the forest district. Trees assigned to individual risk factor classes may belong to the group of damaged or undamaged trees. This assignment scheme enables the specification of a share of the area of damaged trees in each class. The relation between the share of damage in a stand risk factor class and the average value in this factor class constitutes the basis for the assessment of the correctness of the operation of the risk model.

## Results

Cyclone “Xaver” caused severe damage in forest districts in the form of broken, fallen, and snagged trees. For tree stands in forest districts under Regional Directorate of State Forests in Szczecinek, the volume of broken and fallen trees is 477,000 m<sup>3</sup>, that of snagged 247,000 m<sup>3</sup>, the total 724,000 m<sup>3</sup> (Table 3). The most extensive damage was in pine stands (49.6%), owing to their large share in the investigated Directorate. A relatively large share of damage relates to spruce stands (37.5%), and a considerable amount of snagged trees observed in those stands proves the destruction of spruces in this part of the country.

**Table 3.** The amount of wood from fallen trees in the Regional Directory of State Forests of “Szczecinek” after the “Ksawey” hurricane.

Tree species	Amount of deadwood from fallen trees		Amount of deadwood from standing trees		Total amount of deadwood	
	(*1000 m <sup>3</sup> )	(%)	(*1000 m <sup>3</sup> )	(%)	(*1000 m <sup>3</sup> )	(%)
Pine	506.0	63.8	163.0	42.5	669.1	56.9
Spruce	143.5	18.1	174.0	45.4	317.5	27.0
Larch	8.3	1.0	1.3	0.3	9.6	0.8
Beech	30.6	3.9	4.9	1.3	35.5	3.0
Oak	18.1	2.3	10.0	2.6	28.1	2.4
Birch	46.8	5.9	4.2	1.1	50.9	4.3
Alder	8.6	1.1	3.0	0.8	11.6	1.0
Other	31.2	3.9	23.1	6.3	54.1	4.6
Sum	793.1	100	383.5	100	1176.6	100

In the analyzed forest districts, the amount of damage measured by volume ranges from 1,000 m<sup>3</sup> to 69,700 m<sup>3</sup>, and that of broken and fallen trees ranges from 500 m<sup>3</sup> to 44,300 m<sup>3</sup>. In one forest district, the acquired volume of broken, fallen, and snagged trees were below 1.000 m<sup>3</sup>, which may be considered minor damage. In four forest districts, the volume exceeded 40.000 m<sup>3</sup>, which constitutes substantial damage (Fig. 2). These four forest districts are located close to the Baltic Sea.

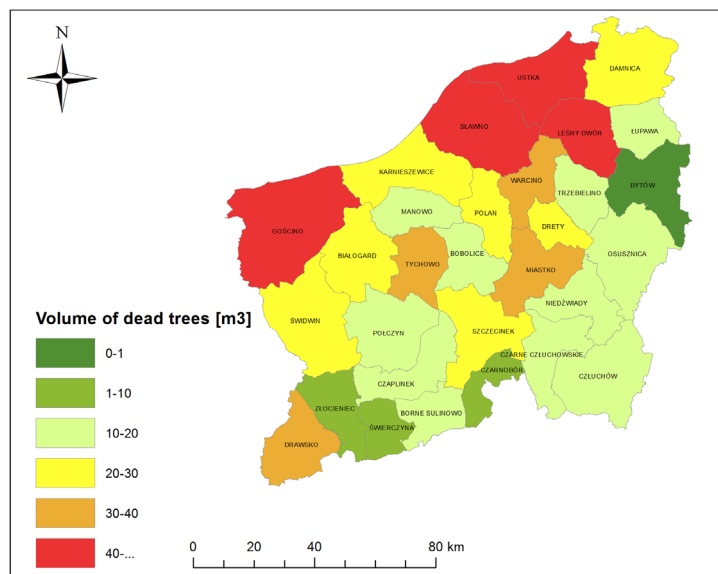
The application of the tree stand damage risk model has been presented based on the Ustka Forest District, which is incorporated in Regional Directorate of State Forests in Szczecinek. The main forest-forming species in the Ustka Forest District, located near the Baltic Sea, are pine (59.0% share), beech (15.1%), birch (10.9%), alder (4.9%), and spruce (4.3%). The primary forest habitat types are fresh mixed coniferous forest (23.7%), fresh hardwood forest (22.4%), and fresh mixed hardwood forest (18.1%). The distinctive feature of the forest district is a relatively high share of dry coniferous forest (4.5%). The average age of the tree stand was 65 years, and the average volume, obtained in the growth model, was 281 m<sup>3</sup>/ha with an increase in volume of 8.8 m<sup>3</sup>/ha/year (Bruchwald, 1986). In December 2013, Cyclone “Xaver” damaged tree stands. The damage was estimated by the volume of acquired broken, fallen, and snagged trees at 44,000 m<sup>3</sup>. Mainly pine and spruce stands were damaged. Dealing with the hurricane consequences lasted through the years 2013 and 2014.

The tree stand damage risk model was applied to estimate risk factors and shares of tree stand area in each

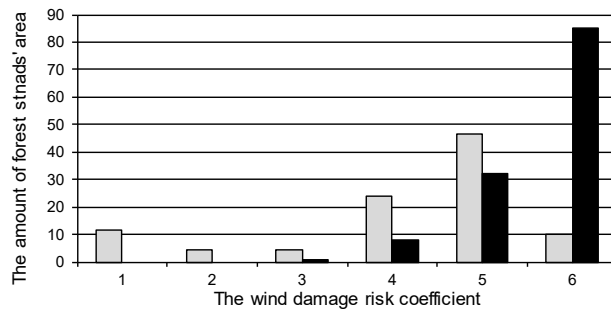
factor class. The greatest risk factor shares’ (43.5%) were in Class 5, Class 4 (26.2%), Class 1 (11.8%), and Class 6 (9.4%) (Fig. 3). The greatest share of damaged tree stands was in Class 6 (85.2%); the lower the class, the less the share (Fig. 3). In Class 1, no damaged tree stands were estimated, and the share in was insignificant in Class 2. The very high-risk tree stands are prone to damage from clusters in several places, which increases the risk of large area damage in the event of another hurricane (Fig. 4).

The correlation between the share of damaged tree stands in damage risk factor classes and the average values of its classes depends on the share of area of damaged tree stands in a forest district ( $U_n$ ). For forest districts under the Regional Directorate of State Forests in Szczecinek, the share  $U_n$  ranged from 0.3% to 25.4%, and the average value was 11.5%. Based on earlier studies (Bruchwald & Dmyterko, 2011), the share may be presented in 5 classes, characterized by the level of damage in the tree stands of the forest district: Class 1:  $U_n < 10\%$  (slight damage); Class 2:  $10 \geq U_n < 20$  (increased); Class 3:  $20 \geq U_n < 30$  (moderate); Class 4:  $30 \geq U_n < 40$  (high); and Class 5:  $U_n \geq 40\%$  (very high).

Forest districts under the Regional Directorate of State Forests in Szczecinek were in the first three classes of damage characteristics: 14 forest districts in Class 1, 13 forest districts in Class 2, and only three forest districts in Class 3 (Fig. 5). From this finding, it can be observed that Cyclone “Xaver” caused relatively little damage to tree stands in the individual forest districts. Forest districts with the greatest share of damaged tree stands form a cluster at the Baltic Sea.



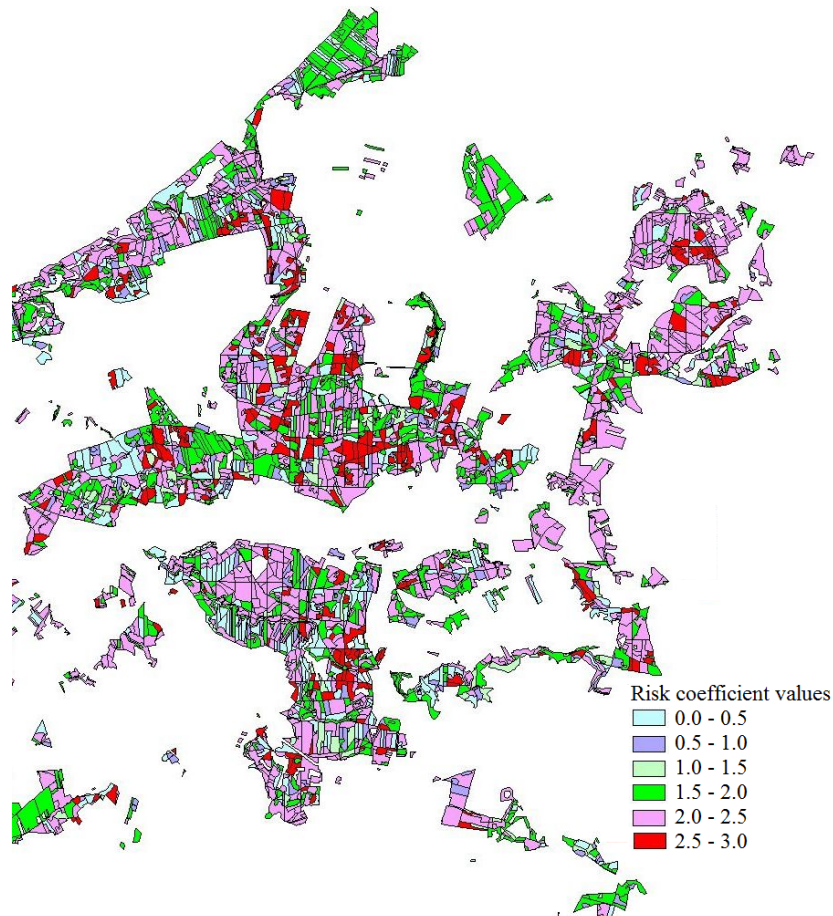
**Figure 2.** The amount of deadwood from standing and fallen trees in the forest districts of Regional Directory of State Forests of “Szczecinek” (2014).



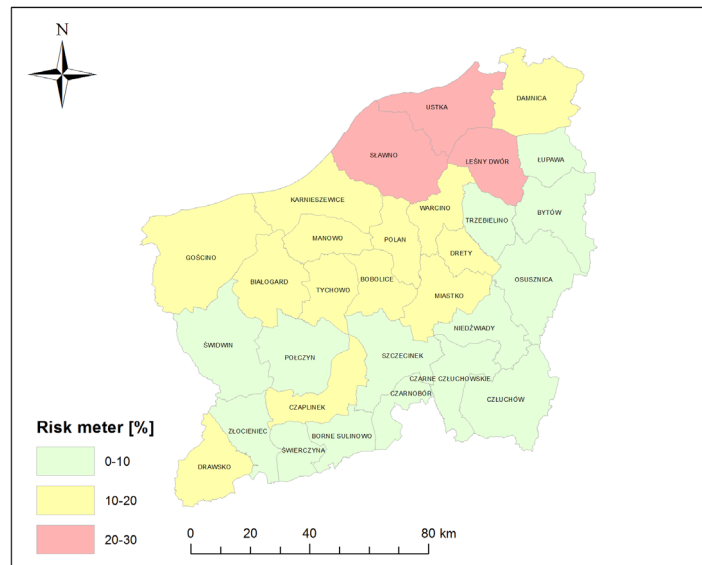
**Figure 3.** The amount (%) of forest stands' area (grey solid) and the amount (%) of forest stands' area damaged (black solid) in the particular classes of wind damage risk coefficient in the "Ustka" forest district (2014).

A correlation was observed between the share of damaged tree stands in a tree stand damage risk factor class and the level of tree stand damage in the forest district (Fig. 6). A higher value of damage level was accompanied by a greater share of damaged tree stands in a class. The strength of this relationship depends on the class number. In Class 1, there were no damaged tree stands, and in Class 2 the share is small and not well-

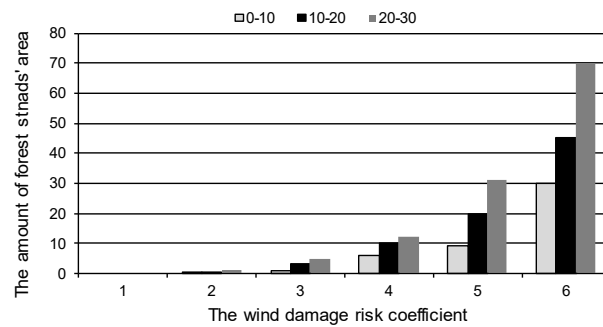
diversified. Per the linear correlation index, there was a significant relationship between the share of damaged tree stands in a class and the level of damage to tree stands in a forest district in the remaining classes (3, 4, 5, and 6) when the adopted significance level was 0.05. It was also estimated that a higher class corresponds to a higher value of the linear regression direction index, from a value of 0.03 in Class 2 to 2.37 in Class 6.



**Figure 4.** The forest stands in "Ustka" forest district (eastern part) with different wind damage risk coefficient values.



**Figure 5.** The amount (%) of forest stands’ area damaged by the wind in the particular forest districts of the Regional Directory of State Forests of “Szczecinek” (2013).



**Figure 6.** Mean values of the amount of damaged forest stands’ area in the particular classes of the wind damage risk coefficient (including the volume of damaged forest stands).

## Discussion

At the end of the last century in Poland, studies were conducted regarding the impact of wind on forests (Zajączkowski, 1991). This research was mainly related to the resistance of trees in a stand to the action of abiotic agents, including wind and snowfall. These study results contributed to the development of support and care methods for tree stands, resulting in more stable tree stands (Stępień, 1986; Zajączkowski *et al.*, 2004; Zachara, 2006; Gil & Zachara, 2006).

In the 1990s, research programs to build trees and tree stand stability models were executed. These programs resulted in the development of snow and wind resistance models for tree groups in a tree stand (Valinger & Fridman, 1998, 1999; Saunderson *et al.*, 1999; Zachara, 2006). Also, more complicated models

were developed to estimate the risk of tree stand damage by wind in relation to its location (Peltola & Kellomäki, 1993; Zawila-Niedźwiecki, 1994a,b; Peltola, 1996; Ni Dhubhain *et al.*, 2001; Koziński & Nienartowicz, 2006).

The SILP has been operating in each of 430 state forest districts in Poland since 2004. The system records information regarding the features of every tree stand, including its area, forest habitat type, species composition, the age of tree groups, their average diameter at breast height (DBH), and height. Critical are also data regarding the volume of wood raw material acquired from individual tree stands and from single trees, including information regarding the possible assignment of different types of tree damage, *i.e.*, broken, fallen, or snag trees.

Data provided by the SILP enabled the execution of this research program, the purpose of which was to



develop a risk model of tree stand damage by winds. The full version of such a model, relevant for lowland as well as mountain areas, was developed by the Forest Research Institute (Bruchwald & Dmyterko, 2013).

The risk model of tree stand damage by winds is not a climate model. Thus it does not assume time and place of wind occurrence and its characteristics. The model specifies the probability of damage in a tree stand if blowing winds are sufficiently strong. The probability corresponds to a damage risk factor indicated by the model, which adopts values from 0 to 3. A higher risk value index means a greater likelihood of damage in a tree stand.

The presented risk model of tree stand damage by winds is the first of its type in Poland. This model considers eight features of a tree stand for lowland areas and 11 features for mountains. Features having the greatest impact on the probability of damage by winds are average height of a tree stand, species composition, location of the forest district in the country region, and level of damage in the previous 10 years; for mountains, it is the altitude of the tree stand above sea level.

The development of a risk model of tree stand damage by winds was based on the volume of broken, fallen, and snagged trees from tree stands of forest districts hit by Hurricane "Pio" in November 2004 and "Kyrill" in January 2007. The empirical material, describing damage in tree stands caused by winds in the later years, served to evaluate the risk model of tree stand damage and to identify opportunities in which to apply the model (Bruchwald & Dmyterko, 2011, 2012).

The evaluation of the risk model of tree stand damage by winds was performed based on data from forest districts managed by the Regional Directorate of State Forests in Szczecinek, where Cyclone "Xaver" hit in December 2013. Damage in tree stands was relatively small, and the greatest volume of acquired broken, fallen, and snagged trees, constituting 70.000 m<sup>3</sup>, was in the Sławno Forest District. Earlier hurricanes caused much greater damage in certain forest districts, *e.g.*, in Przedbórz Forest District (Regional Directorate in Łódź) where the acquired volume of broken, fallen, and snagged trees exceeded 300.000 m<sup>3</sup> (Janusz, 2008).

The share of damaged tree stand area in forest districts adopts a value from 0 to 100%. It is related to the share of damaged tree stand volume in the forest district. This relationship may be disturbed by a damage distribution that is characterized by a significant volume of damaged trees located in a relatively small area, which usually faces the direction of the storm force.

The degree of tree stand damage in a risk factor class strongly correlates to the share of damaged tree stands in a forest district. This correlation refers to third and higher classes. The higher share of damaged tree stands

in a forest district is accompanied by higher values of, and greater diversification of damaged tree stands in, classes of damage risk factor.

In this paper, the risk model of tree stand damage was presented. This model applies to lowland and mountain areas. The model specifies the range of tree damage risk factors from 0 to 3, which refers to the probability of damage occurrence in a tree stand. The most endangered are tree stands where the value of risk factor is close to 3.

The risk model of tree stand damage was evaluated based on data related to damage caused by Cyclone "Xaver" in tree stands. The greatest damage occurred in tree stands with the highest tree stand damage risk factor. This relationship was even stronger if the share of damaged tree stands was greater in the forest district. Therefore, the evaluated model has been verified successfully.

The risk model of tree stand damage by winds uses data provided by the SILP. The model has been developed in compliance with this System; therefore, it can be applied and used at every level of forest administration.

The SILP includes, among others, forest digital maps for every forest district. With the model program, it is possible to obtain presentation maps for every tree stand and their damage risk factors, marked with an appropriate color. Therefore, it is feasible to get data on the spatial configuration of threats to tree stands in a forest district. The concentrated layout of high-risk tree stands is unfavorable, as it may lead to massive damage in a forest in case of sufficiently high winds.

Currently, the application of the risk model of tree stand damage by winds may be recommended for qualifying tree stands for wood harvest plans. Such tree stands which are characterized by a high-risk factor of tree stand damage should be first in line for consideration.

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