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Spatial distribution of damages caused by wind storms in treestands of the Tuchola Forest

Grzegorz Koziński, Andrzej Nienartowicz

Institute of Ecology and Environment Protection
Laboratory of Ecological Modelling
Nicolaus Copernicus University, Gagarina 9, 87–100 Toruń, Poland
e-mail: nienart@biol.uni.torun.pl
gkozinsk@biol.uni.torun.pl

Abstract. This paper presents the application of Geographical Information System in the analysis of spatial distribution of wind-induced damages in the forest landscape. Those damages were caused mainly by hurricanes, which took place on the 26th of December 1999 and 22nd of June 2000. Location and extent of damages were determined in the whole territory of the Tuchola Forest region in Northern Poland. The analysis of influence of the landscape structure and history of land use on localization and frequency of occurrence of root and stem breakages was carried out at four sites delimited in forest inspectorates Woziwoda, Przymuszewo and Czersk as well as in the Bory Tucholskie National Park, where the extent of damages was the highest one.
The aim of this work was to find answers to four questions: 1 – does a closer location of forest towards a field-forest boundary increases the extent of damages in a forest stand?, 2 – are wind-induced damages more severe in secondary forests reconstructed on formerly arable lands than in forests, the development of which was not interrupted by temporal agricultural land use after cutting down the trees?, 3 – what influence has the terrain orography on the intensity and extent of wind-induced damages? 4 – to what extent root throws and stem breakages change the canopy structure?
In order to determine changes in the extent and distribution of the forest and agricultural area in the study terrain as well as to identify secondary forests, old and contemporary topographic maps were used, as well as forest economic maps, satellite images Landsat 7ETM+ dated 2000 and Ikonos dated 2003. Information derived from the above mentioned sources as well as data obtained from forest stocktaking and direct field measurements carried out with the GPS receiver, were arranged in the geographic information system.
The statistical analysis conducted with the GIS technology, applying computer programs MicroStation/Bentley, ESRI ArcView3.2 and Idrisi 32, proved that factors such as neighbourhood of large non-forest areas as well as temporal agricultural use of forest soils indeed increase the extent and frequency of occurrence of damages caused by strong wind in the canopy of forest ecosystems.

Key words: canopy, database, digital elevation model, GIS, GPS, forest edge, landscape, remote sensing, secondary forest, spatial pattern, windthrow.

1. Introduction

In recent years in many forest inspectorates of the Tuchola Forest, being one of the biggest forest complexes in Poland, an increase of wind-induced damages can be noted. The highest losses in treestands resulting from this ecological factor took place in the northern part of the aforementioned region at the end of 1999. They were related to effects of the hurricane, which descended upon Western and Central Europe on the 26th December. This hurricane, described in the meteorological and ecological literature as "Lothar" (Wesp 2000; Clarke 2001; Pearce et al. 2001; Ulbrich et al. 2001; Mayer

& Schindler 2002; Braun et al. 2003), brought about considerable damages mainly in forests of Germany, France, Switzerland and Austria. In the Tuchola Forest, the most severe damages of forest ecosystems resulting from this hurricane were recorded in the Forest Inspectorate Przymuszewo. Those were stem and root breakages of single trees. Surface damages were not observed.

The second significant hurricane occurred in the Tuchola Forest half a year later, i.e. the 22nd of June 2000. It brought about surface root and stem breakages. This kind of damages occurred mainly in Forest Inspectorates of Czersk and Woziwoda, which are included in RDLP of Toruń (Regional Directorate of the "State Forests" Holding).

From the preliminary analysis of the spatial distribution of injuries, it follows that location of root and stem breakages corresponds with the distribution of secondary forests, i.e. reconstructed on formerly arable lands, which in the recent past were agriculturally used. According to Gorzelak (1999) in forests on formerly arable lands the destructive activity of wind is enhanced by a poorly developed root system of trees and their wholesomeness weakened by pathogens. Also close vicinity of non-forest areas, i.e. larger areas of agricultural fields, meadows and pastures, as well as bigger mid-forest lakes, could have some influence on the type and extent of wind-induced injuries.

The present work aimed at verifying the above hypotheses at three study sites: 1 – in the vicinity of the locality Komorza Wielka in the Forest Inspectorate Woziwoda, 2 – in the Bory Tucholskie National Park, 3 – in the valleys of Lake Trzemeszno and the River Brda in the Forest District Okręglik, the Forest Inspectorate Czersk. Stem and root breakages occurred here mainly nearby the field-forest boundary as well as in the vicinity of big lakes, and also within fragments of forest areas, of which a considerable part is constituted by secondary forests reconstructed on formerly arable lands. When analysing the distribution of wind-induced injuries, the stock-taking data on wind-fallen trees and logged timber were used, as well as data from old and contemporary cartographic materials and measurements taken with the GPS receiver, and also there were applied methods of satellite remote sensing and modelling of ecological phenomena with the GIS technology.

2. The study area

2.1. General characteristic of the Tuchola Forest

The Tuchola Forest is situated in northern Poland and constitutes one of the subregions of Pomerania (Kondracki 1978; Atlas Rzeczypospolitej Polskiej / Atlas of the Republic of Poland 1993–1997). It is a vast territory located west of the Lower Vistula, within the drainage basin of the rivers Brda and Wda. The area of this subregion amounts to ca. 5000 km^2. A vast outwash plain at the foreland of terminal moraines from the Pomeranian stage of the last Baltic glaciation is a dominating geomorphological form there. The surface of the outwash plain is cut through by postglacial gullies, which are filled with numerous lakes and rivers. Low-fertile soils are predominating there, developed mainly from poor sands. The main vegetation formation are fresh and dry pine forests. According to Boinski (2002), in the syntaxonomic classification they are included among associations Leucobryo-Pinetum, Peucedano-Pinetum and Cladonio-Pinetum. Smaller areas are covered with other types of pine forests: ericaceous pine forest Calluno-Pinetum, moist pine forest Molinio-Pinetum and marshy pine forest Vaccinio uliginosi-Pinetum on organogenic soils.

In the remote past, deciduous species had a higher contribution in treestands, also on poorer habitats where nowadays Scots pine strongly dominates. Oak-hornbeam forests, oak and beech forests covered larger areas than nowadays, but lasting for several centuries anthropopressure caused they were transformed into agricultural lands and heathlands, or replaced by pine monocultures. The most significant changes in the character of the forest stand followed on the turn of the 19th century when the Prussian forest administration extensively planted the thinned out forest lands and degraded arable soils with pine. Also heathlands, fallow lands, degraded pastures and wastelands were afforested. A further increase of the forest area followed after the year 1920 when most of the Tuchola Forest region was included within the borders of the reborn Polish

State. The subsequent afforestation period of the formerly arable lands and waste lands followed after the 2nd World War when within the framework of the so called land reform, large estates were partially parcelled out and donated to individual farmers and partially included in state forests and afforested, mainly with pine. Afforestation of formerly arable lands takes place also today, as unprofitableness of farming conducted by employees of forest inspectorates on small mid-forest plots leased from state forests, causes that their tenants cease the cultivation. Usually, although not always, after several years of laying fallow those areas are afforested (Kunz et al. 2000; Nienartowicz et al. 2002).

At present, the forestage of the Tuchola Forest subregion fluctuates around 50%, of which pine forest stands constitute an absolute majority (Boinski 1999). They developed from artificial regeneration, mainly planting, on poor sandy soils, not suitable for cultivation. They mostly belong to middle age classes. Treestands older than 100 years occupy a small area.

Deciduous forests belong to syntaxa Tilio-Carpinetum, Galio-Carpinetum, Stellario-Carpinetum, Aceri-Tilietum, Calamagrostio-Quercetum petraeae, Luzulo pilosae-Fagetum and occur in river valleys, mainly the Brda and Wda as well as their tributaries, where also birch forests Betuletum pubescentis, elm forests Ficario-Ulmetum and alder forests occur Ribeso nigri-Alnetum, Circaeo-Alnetum, Poo trivialis-Alnetum, Stellario-Alnetum. Many deciduous forests are covered with the reserve protection. In uplands, besides fresh and dry pine forests, degradation forms of deciduous forests occur, developed through introducing pine in more fertile habitats. Those are so-called pine coppices, dominated in the herb layer by the following species: Arrhenatherum elatius, Agrostis vulgaris, Deschampsia flexuosa, Pteridium aquilinum (Boinski 2002).

To recapitulate one can state that the present-day condition of forests in this region was influenced, to a large extent, by three processes: 1 –displacement of forest into the most poor habitats, 2 – impoverishment of species diversity of treestands as a result of routine forestry, 3 – afforestation of deforested territories in "successive surges" together with simultaneous simplification of the canopy species composition.

2.2. Characteristics of the study sites

Two spatial scales and two levels of resolution were applied in order to study the distribution of damages caused by wind in the Tuchola Forest. The first level was constituted by the whole region and a forest inspectorate was the basic unit in the general analysis of damages. The second level was constituted by small areas where, however, wind-induced damages in treestands were highest in the whole region. Those areas were selected on the basis of results obtained from the analysis carried out at the first level. The selected territories were the study areas used for detailed analyses of the influence exerted by the landscape structure and land use history on the distribution and extent of damages. The basic unit in detailed analyses conducted at the second level was a forest subdivision.

2.2.1. General studies

The research area at the first level were operational regions of 22 forest inspectorates, which at least partially are included in the nature-forest province of the Tuchola Forest according to Trampler et al. (1990). As regards the organization, they belong to three Regional Directorates of the "State Forests" Holding (RDLPs): Gdańsk (Lipusz, Kościerzyna, Kaliska, Lubichowo), Szczecinek (Bytów, Osusznica, Miastko, Bobolice, Niedźwiady, Człuchów, Czarne Człuchowskie, Szczecinek) and Toruń (Dąbrowa, Osie, Trzebciny, Tuchola, Woziwoda, Rytel, Czersk, Przymuszewo, Zamrzenica and Różanna). The research also covered the territory of the Bory Tucholskie National Park. In order to compare the damage extent, observations were also conducted in forest inspectorates neighbouring with the Tuchola Forest Province, especially from the south-eastern side, i.e. in the territory of RDLP Toruń.

2.2.2. Detailed studies

Three sites were selected for the detailed studies. The first site was constituted by marginal fragments of forests at the boundary with cultivation fields and meadows in the Forest District Komorza (the Forest Inspectorate Woziwoda). A forest fragment studied regarding the spatial distribution of wind-induced damages is situated in the buffer zone of the Tuchola Landscape Park. It is situated north-east of Tuchola on both sides of the national road no 237. The forest adjoins to vast agricultural area.

The object analysed covers a strip of forest extending from the field-forest boundary along the distance of approximately 2 km towards the forest interior. This zone circumvents the village Raciąż and runs north-west through the neighbourhood of the village Wielka Komorza towards the vicinity of the town Tuchola. A considerable part of this zone is constituted by secondary forests on formerly arable lands. From the north-west towards the south-east the River Brda runs, in places almost parallel to the field-forest borderline. In the past, the river constituted the border between the forest complex and the agricultural area. After the 2nd World War the territory on the right riverside was afforested. This causes the border was shifted few metres westwards.

The second site is constituted by the Bory Tucholskie National Park, situated on the eastern side of Lake Charzykowskie. This water body is one the biggest Polish lakes. In the vicinity of its northern part, another big water reservoir is located – Lake Karsińskie. In the park area of 4,798.23 ha, forest communities strongly dominate (83%) in the structure of land cover. Water reservoirs take the second place on this list and cover 11% of the park area. From the analysis of historical cartographic maps it follows that in the past, the territory of the national park was mostly afforested. Minor deforestation events, brought about by the economic activity of man, took place only along the northern side of the flow-through lakes' series, called Struga Siedmiu Jezior (the Stream of Seven Lakes). In the analysed area, already before the creation of the national park, forest fellings were reduced. For this reason, in the present-day structure of forest stands, higher age classes have a significant share. Scots pine is an absolute dominant among tree species. The oldest and most robust pine forest stands occur in the central part of the national park, in the vicinity of Lakes Gacno Małe and Gacno Wielkie, and on the western side of Lake Ostrowite. Pine forest stands overgrow here quite distinct terrain elevations.

The third study site is located within the thick forest complex in the territory of the Forest District Okręglik, within the Forest Inspectorate Czersk. The study area is located south of the Bory Tucholskie National Park and east of the highroad Chojnice–Brusy–Kościerzyna. Observations covered two territories. The first one includes forests located within the lake gully constituting a natural extension of the lakes' series: Dybrzk, Kosobudno, Trzemeszno. The second place of detailed analyses was a fairly large valley of the River Brda flowing through Lake Kosobudno. In the lake gully and the river valley, alike in uplands, fresh pine forests dominate, with forest stands mostly from average age classes. Terrain depressions located at water reservoirs are overgrown with alder forests.

3. Methods

The research was performed on the basis of the geographic information system of the Tuchola Forest. At the first stage, a set of rectangular coordinates was designed in the 1965 system. Next, sheets of topographic maps in the scale of 1 : 25 000 were scanned and fitted in by means of the program MicroStation 95 with the overlay Descartes. In the process of geometric rectification, those maps were overlaid with the updated forest management map in the scale of 1 : 20 000 as well as historical topographic and forest management maps from the 19th and beginning of the 20th century. Most of the information about the land cover and land use in the past was provided by the map of Schrötter-Engelhardt from the turn of the 18th century as well as the forest management map of the Prussian Königlichen Oberförsterei Chotzenmühl dated 1896. Also a satellite image Landsat 7 ETM+ dated May 2000 was fitted into the system of coordinates as a raster information layer.

In order to define the spatial distribution of secondary forests on formerly arable lands and places where forest was continuously present during the last several centuries, on the basis of the satellite image, a map of spatial variation NDVI was created, as a separate information layer. Values of NDVI were calculated according to the formula:

$$NDVI = [IR - RED] / [IR + RED],$$

where RED and IR stand for spectral response of particular pixels of the study area image obtained with the scanner Thematic Mapper for the channel 3 (RED, 630–690 nm) and the channel 4 (IR, 760–900 nm). In order to calculate NDVI and generate maps of spatial diversification of this index, the program IDRISI was applied.

By applying the GIS technology, spatial relations were defined between the distribution of colours used on the map of NDVI spatial variation and the location of secondary postagricultural forests on contemporary and historical topographic maps and forest economic maps.

On the prepared raster layers, after x 1000 rescaling, current forest districts and subdistricts were digitalized in the program ArcView 3.2 ESRI. The distribution of wind-induced damages in the study area was charted by means of the GPS receiver (Smart Antenna with the software Termap). Location coordinates of root and stem breakages were imported into the project by means of the XYZ module in the program MicroStation J/Polish. In the case of surface damages, points along the border of deforested areas were connected into polygons.

The prepared vector layer was connected with the database for the period 1998–2002 coming from the "State Forests" Holding Information System of obtained in the forest inspectorates, on the territory of which the detailed studies were conducted. Information about the distribution of wind-induced damages and the amount of removed timber was also acquired from Management of the Bory Tucholskie National Park. The database included information about the forest address (No. of section and subsection), forest habitat type, stand quality classification, damage type, volume of logged timber in m^3 and date of logging, information about the soil type (post-agricultural, forest soil), the degree of afforestation, name of the main canopy species, its age and quantitative share.

In the case of site 1, i.e. the Forest Inspectorate Komorza, with the help of a module for creating polygons from the program ArcView 3.2, a buffer layer was created comprising 86 zones at 10 m intervals. For calculation purpose, sums of damages in m^3/ha were presented at 100 m intervals. The zones were distributed in the direction from the field-forest borderline into the studied forest complex. The forest borderline was determined on the basis of rectified topographic and management maps as well as digitalized forest sections and subsections. Next, by applying the so-called method of "combined subjects", the buffer layer was merged with the layer of digitalized forest subsections. This was performed on the basis of gravity centres of particular polygons. The overlay Spatial Analyst – GeoProcessing Wizard was applied for connecting the subjects.

From the tables created by this program, data were selected concerning the logged timber volume for a given forest subsection, its area and location in a given buffer zone, i.e. a distance interval from the field-forest borderline. The magnitude of wind-induced damages in m^3 was divided by area of a given forest subsection. Calculated extents of injuries were summed up separately for every buffer zone. Using the table comprising 2 vectors of numbers, i.e. the volume of logged timber in m^3 per ha and the distance of every 86 buffer zones from the field-forest boundary in meters, a correlation coefficient was calculated as well as a function expressing the relation between those parameters was defined. In the calculations computer programs Statistica and Curve-Expert were used.

Using the information about every forest subdivision for the site Komorza and applying the method of "combined subjects", also the analysis of relationships was performed between the damage extent and the habitat type and tree species in the canopy.

In the case of the study polygon Bory Tucholskie National Park, the distribution of root throws and stem breakages, determined by means of the GPS receiver, was plotted upon the digital map of this nature object. Next, upon this information layer, the satellite image Ikonos dated August 2003 was superimposed. The satellite image was done with the field resolution of 4 m in the multispectral mode and 1 m in the panchromatic mode. The relation was determined between the number of root throws and mosaicness of tree canopies described on the basis of the normalized vegetation index NDVI. Also comparisons were performed between mosaicness of the tree canopy image from the national park and the area situated outside the park, on the western side of Lake Charzykowskie, where wind damages during the considered period were small.

For Site 3, i.e. the Forest District Okręglik, a numerical model of the terrain was drawn up. Upon the three-dimensional image of this terrain, positions of both stem and root breakages of single trees were plotted according to GPS readings, and also of the observed surface damages. There were evaluated relations between the occurrence of wind-induced disturbance in the canopy structure and the location of main relief elements, especially the route of river valleys and lake gullies.

Data about the distribution and extent of damages in the areas located outside the three study polygons, selected for detailed analyses, were obtained through distribution of questionnaires to individual forest inspectorates. Whenever required, the obtained information was defined accurately through the website connection and direct contacts with the forest inspectorates staff.

4. Results

4.1. Temporal and spatial variation of damages in the Tuchola Forest area

On the basis of data supplied by forest inspectorates, it was ascertained that during the years 1998–2002, logging of timber from stem and root breakages amounted to 602,000 m^3. Out of this amount, 57.8% was constituted by timber removed in 2000. Such intensive logging of timber in 2000 was brought about by damages induced by two hurricanes, i.e. "Lothar" on the 26th of December 1999 and removed in the early part of 2000, as well as damages being after-effects of the windstorm on the 22nd of June 2000 and removed in the latter part of 2000.

In total in 2000 logging of timber from root and stem breakages in forest inspectorates belonging to the Tuchola Forest nature-forest district, amounted to 347,931.74 m^3. Out of this amount, in RDLP Toruń 109,720.56 m^3 was logged, in RDLP Gdańsk 81,586.66 m^3, in RDLP Szczecinek 156,624.52 m^3 (tab. 1).

During the whole analysed 5-year period, the least logging of timber from wind damages was done in 1998. It constituted 3.59% of the logging from 2000. Quite a lot of timber from wind damages was obtained in 2002. The calculated sum for this year constituted 49.73% of the timber obtained in 2000.

Table 1. Wind damages measured by the amount of timber (m^3) removed in 1998–2002

Year	The Regional Directorate of State Forests			The Tuchola Forest Total
	Toruń*	Gdańsk	Szczecinek	
1998	796.66	9,871.27	1,815.91	12,483.84
1999	4,652.05	18,533.37	9,005.69	32,191.11
2000	109,720.56	81,586.66	156,624.52	347,931.74
2001	14,047.16	15,215.94	7,009.30	36,272.40
2002	64,221.58	31,691.21	77,123.35	173,036.14
Σ	193,438.01	156,898.45	251,578.77	6,010,915.33

* including the Bory Tucholskie National Park

Logging of timber from root and stem breakages recalculated per one forest inspectorate in 2000 amounted to 15,815.01 m^3. In 1999 and 2001 the average logging per one forest inspectorate was 9–12 times lower than in 2000 and amounted to 1,363.85 m^3 and 1,727.26 m^3 respectively.

The highest logging of timber from wind damages in 2000, amounting to 52,000 m^3, was recorded in the Forest Inspectorate Bytów. Volumes significantly exceeding the average volume of 16,000 m^3 were also recorded in Forest Inspecto-rates Lipusz, Miastko and Szczecinek. Those were 32, 33 and 37.5 thousand m^3 of wood respectively. Amounts of wood above the annual average were obtained also in the Forest Inspectorates Rytel and Czersk, that is 29 and 23 thousand m^3 of wood. The amount of wood, closest to the average volume, was obtained from root and stem breakages in the forest inspectorates Woziwoda and Przy-muszewo, 13 and 18 thousand m^3 of wood, respectively.

It follows from the above data that two out of three research polygons, analysed in detail, are situated within or in the vicinity of state forest economic units where damages caused by the destructive wind force were most similar to average values. In the Forest Inspectorate Rytel, which in the past included part of the territory of the Bory Tucholskie National Park, logging of wood from root and stem breakages was clearly higher than the average value per one forest inspectorate.

Figure 1. The distribution and extent of wind damages measured by the volume of logged timber in the Tuchola Forest and neighbouring areas in 1998–2002 (1 – timber logging in m³/year in subsequent years, 2 – selected forest inspectorates with polygons for detailed studies, 3 – other forest inspectorates within the Tuchola Forest, 4 – other forest inspectorates outside the Tuchola Forest)

Changes in the amount of wood obtained during the years 1998–2002 according to forest inspectorates are presented in fig. 1.

Histograms presented in figure 1 and also values quoted in table 1 indicate that the most severe damages in 2000 occurred in the western part of the Tuchola Forest District. Timber logging from root and stem breakages in eight forest inspectorates of RDLP Szczecinek constituted 45.02% of the total damage. The remaining nearly 55% consisted of timber removed in 14 forest inspectorates from RDLP Gdańsk and RDLP Toruń. It was 23.45% and 31.53%, respectively, of the timber logged from root and stem breakages in the whole territory of the Tuchola Forest in 2000.

4.2. Influence of the field-forest boundary and past economy on the spatial distribution of damages

The total area of forest subsections included in the study site of the Forest District Komorza amounted to 1,682.62 ha. Based on the analysis of data coming form historical forest stocktaking, old topographic maps and forest economic maps as well as a satellite image from the year 2000, it was established that secondary postagricultural forests covered the area of 833.85 ha, what constituted 50.77 % of the study area. Forests on the soils, which were not agriculturally used in the past, covered 808.6 ha, that is 49.23 %. They were located in the heart of the forest complex. Near the field-forest border, secondary forests occurred (fig. 2).

Three surface damages of 0.23 ha, 0.44 ha, 0.53 ha as well as several hundred of single root and stem breakages resulted from the 22 June 2000 hurricane impact, were recorded at the Komorza study site. The total volume of wood obtained from those damages amounted to 4,478.62 m³. Out of this, 3,831.73 m³ was obtained in forests on formerly arable soils and 646.89 m³ on forest soils. When recalculating per ha of a forest category, those numbers amounted to 4.59 m³/ha and 0.80 m³/ha respectively. Injuries in secondary forests on formerly arable soils, constituted 84.37% of losses.

In the obtained volume, pinewood significantly dominated, making up 92.64% of the total. Beech wood represented 4.48%, alder wood – 1.35%, birch wood – 1.35%, and oak wood only 0.17%. The percentage share of deciduous species in the logged timber was lower than their share in the total biomass of the forest stand growing at the entire research area Komorza. This confirms high resistance to wind activity of species from genera like beech or oak.

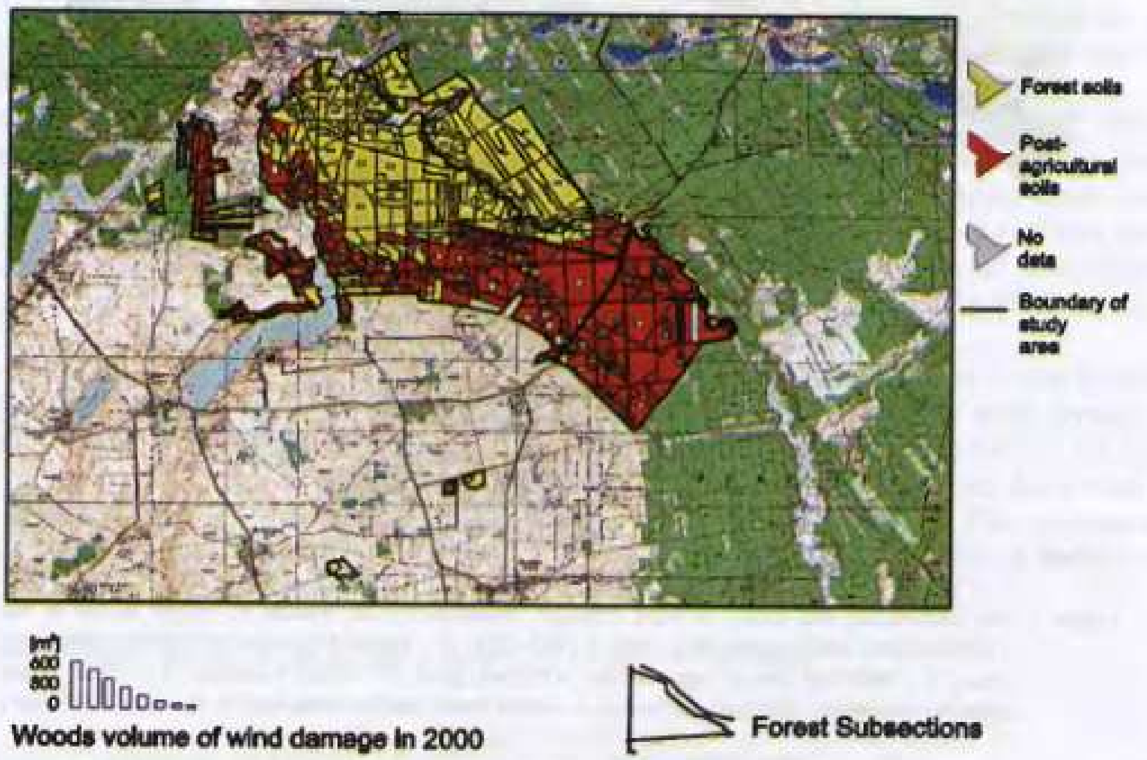

Figure 2. Spatial distribution of secondary forests on formerly arable lands and on forest soils, division of the study area into forest subsections and volume of timber obtained from stem breakages in particular subsections (1 – volume of fallen wood, 2 – boundaries of the study area, 3 – forest lands, 4 – formerly arable land, 5 – areas where quantitative data was not available, 6 – boundaries of the forest subsections)

Most of the wood was obtained from the forest stands of 41–60 years old (41.27%) and 61–80 years old (27.51%). This resulted from the fact that forest stands from middle-age classes occupied the largest area at the Komorza site.

Most of the damages, i.e. 32.76% occurred in the most fertile forest habitats, which adjoined the field-forest border. High fertility of habitats indicates that those were postagricultural forests or pine monocultures replacing previous deciduous forests. As regards the typology, most of the wood was obtained from stem breakages in the habitat of fresh mixed coniferous forest (46.73%), fresh coniferous forest (26.60%) and fresh mixed forest (24.58%).

From the maps prepared in the GIS technology and from the drawn up histograms, it follows that more severe injuries occurred along the field-forest boundary. Along the distance of 860 m into the forest depth, 1,004.92 m^3/ha of timber was obtained from stem breakages within the first 430 m. Within the second zone, i.e. at the distance of 430–860 m, timber logging amounted to only 96.78 m^3/ha. When analysing the buffer zones in 10 m intervals, it was ascertained that most severe damages, in the amount of. 103.09 m^3/ha, occurred within the zone of 290–300 m. At the distance of 140–150 m, it was 65.18 m^3/ha and at the distance of 100–110 m – 62.94 m^3/ha. Within the remaining buffer zones, the timber logging was much lower and did not exceeded 60 m^3/ha. The correlation coefficient expressing the relationship between damages and the distance from the field-forest border (in 10 m intervals) reached the value of –0.6086.

In the analysis carried out in 100 m intervals, it was ascertained that the most severe damages occurred within the zone of 0–100 m (373.49 m^3/ha), then within 200–300 m (264.06 m^3/ha) and 100–200 m (212.71 m^3/ha). Wood obtained within those zones constituted 33.98, 24.02 and 19.35% of the total damage, respectively. In total, within the forest zone at the distance of 300 m, 77.35% of the total damage was recorded. For calculations performed with the spatial interval of 100 m, the function expressing the relationship between the extent of damages and the distance from the field-forest boundary remained as in figure 4.

Figure 3. Volume of the logged timber in successive buffer zones arranged in 100 m intervals from the field-forest border

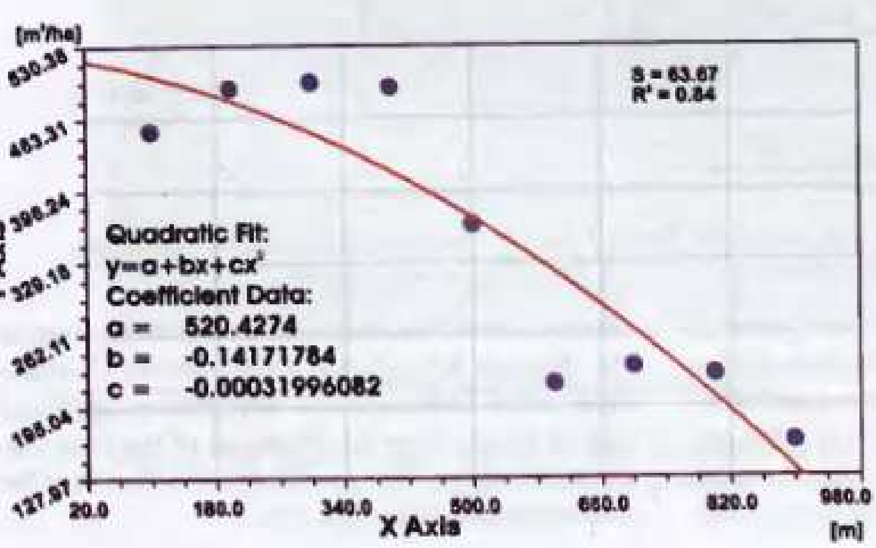

Figure 4. Function expressing the relation-ship between the volume of timber logged and the distance to the field-forest border in 100 m intervals. Axis X – distance to the field-forest border, axis Y – volume of timber logged in m^3/ha

4.3. Influence of big water reservoirs and age of forest stands on the occurrence of stem breakages

This relationship was studied at Site 2, which is the area of the Bory Tucholskie National Park. Surface damages were not recorded here, whereas devastations in the form of root throws and stem breakages of single trees were observed very frequently. The main place of their occurrence was a part of the National Park on the southern side of Struga Siedmiu Jezior (the Stream of Seven Lakes), in the vicinity of Lakes Gacno Małe and Gacno Wielkie (fig. 5). This part of the Park is overgrown by the oldest forest stands, whereas forests secondary reconstructed on soils temporary used for agriculture do not occur. On the map of spatial diversification of the index NDVI for the National Park area, drawn up on the basis of the satellite Ikonos, the heterogeneity of the vegetation cover is the highest in the place where wind damages are most frequent. It is significantly increased by numerous gaps in the canopy caused by single tree falls. This effect can be easily observed when comparing the park area with tree stands undisturbed by the wind factor, located on the western side of Lake Charzykowskie.

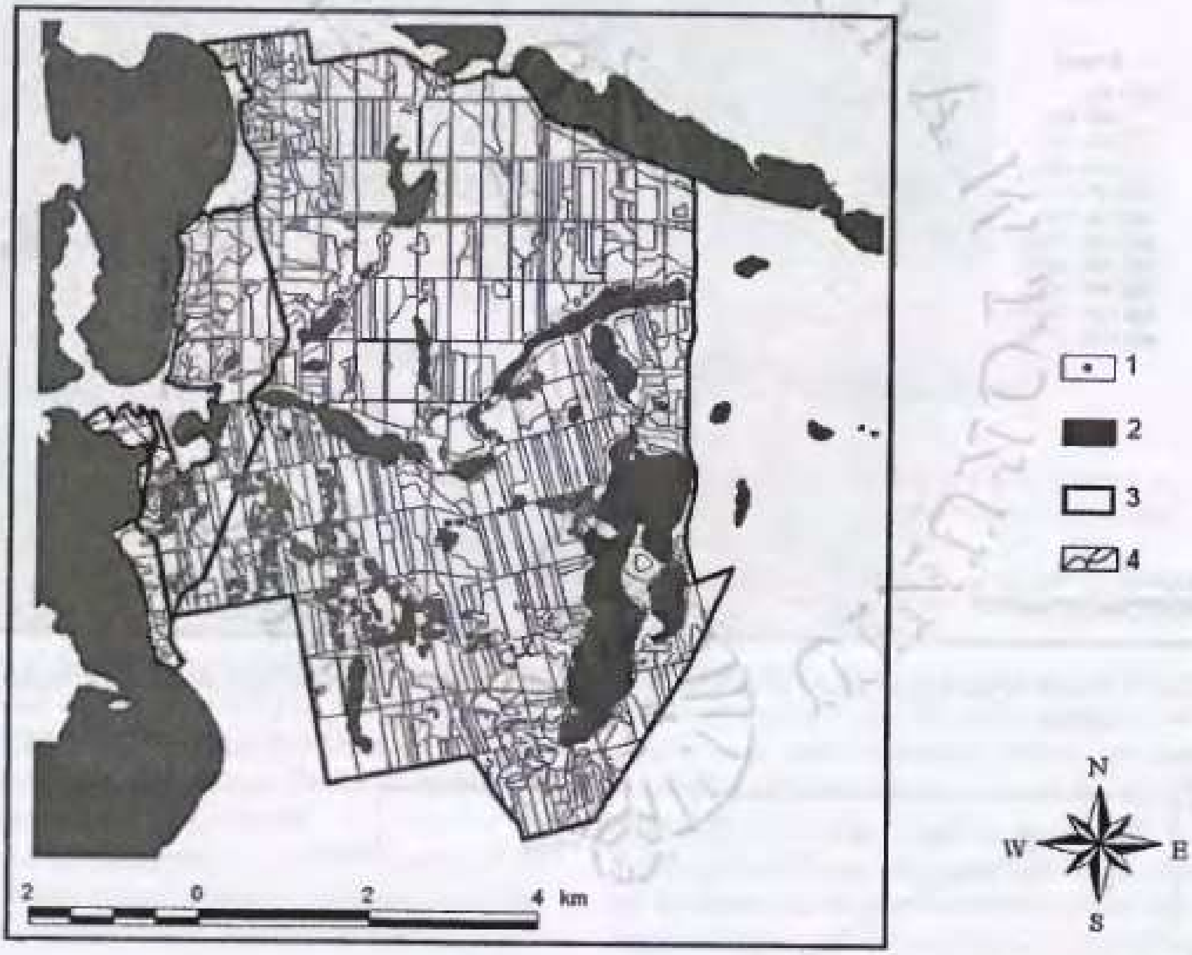

Figure 5. Wind damages in the Bory Tucholskie National Park (1 – location of root and stem breakages, 2 – lakes, 3 – the border of National Park, 4 – borders of forest subsections)

In the territory of the Bory Tucholskie National Park, on the northern side of Struga Siedmiu Jezior (the Stream of Seven Lakes), root throws and stem breakages happened much more seldom, although on the basis of land cover read out from the map of Schrötter-Engelhardt, from the turn of the 18th century, as well as from the management map of the Prussian Königlichen Oberförsterei Chotzenmühl dated 1896, one can state that a significant part of forests from this fragment of the Park was reconstructed on the non-forest lands later than the southern part of the Park.

From the spatial distribution of damages caused by strong winds and presented on the numerical map of the Bory Tucholskie National Park (fig. 5), it follows that root throws and stem breakages occurred more seldom north of Struga Siedmiu Jezior (the Steam of Seven Lakes) than on the southern side. Such differences in the damage distribution occurred despite that fact that west of both the southern and northern part of the Park, big lakes were situated in the close vicinity: Lake Charzykowskie (the southern part of the Park) and Lake Karsińskie (the northern part).

4.4. Influence of the field relief on the spatial distribution of damages

At Site 3, i.e. on the territory of the Forest District Okręglik in the Forest Inspectorate Czersk, where the influence of the terrain orography on the occurrence and extent of wind-induced damages was studied, 10 surface root breakages were recorded (fig. 6). It follows from the numerical model of the terrain that those areas occur mainly in the vicinity of valleys along the extension of the gully of Lake Trzemeszno. However, they do not take up areas in the lowest altitude. In their location, the influence of the generally dominating western wind is revealed, rather than the shifting possibility of fast-moving air masses along lake valleys. As most of the surface root throws are located along the nearly straight line east-west on the eastern part of Lake Trzemeszno.

5. Discussion and conclusions

The ecological literature indicates that during the last thirty years the research on wind-induced damages in forests was conducted on almost all continents. It is because wind is one of the main factors causing disturbances in forests. Schelhaas et al. (2003) report that over the period 1950–2000, an annual average of 35 million m^3 woods was damaged by disturbances; there was much variation between years. Storms accounted for 53% of the total damage, fire for 16%, snow for 3%, and other abiotic causes for 5%. Biotic factors caused 16% of the damage, and half of it was caused by bark beetles. No cause was assigned for 7% of the damage, or there was a combination of causes. The 35 million m^3 of the damage constitutes about 8.1% of the total fellings in Europe and about 0.15% of the total volume of growing stocks (Schelhaas et al. 2003).

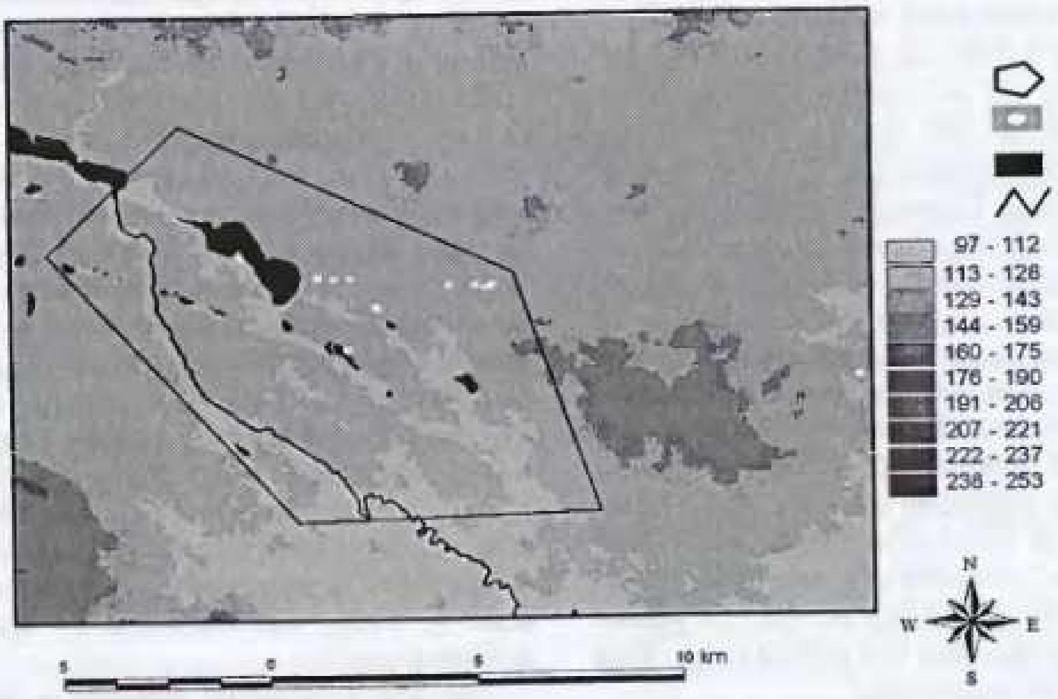

Figure 6. The digital elevation model and surface deforestation in the Forest District Okręglik (1 – the zone with potential occurrence of wind damage, 2 – surface damages, 3 – lakes, 4 – rivers, 5 – altitude [m] above sea level)

Damages caused by wind in forests were often considered by many authors as effects of global climate changes. They were also considered as one of the causes of climatic changes since windthrows contribute to a decrease of forest area and the amount of carbon accumulated in plant biomass. In many studies conducted on those aspects, methods of satellite remote sensing and the GIS technology were applied, including computer programs also used in the present study. This technology and software were applied in the spatial analysis of wind-induced damages, among others by Foster & Goose (1992), Wright & Quine (1993), Lekes & Dandul (2000), Mitchell et al. (2001) as well as Quine & Bell (1998).

With the help of remote sensing methods and GIS, the frequency of stem breakages and wind-induced damages were being compared in forests of diverse history, both natural and forest plantations (Quine et al. 1999). Influence of several diverse factors connected with the vegetation cover on the spatial structure and extent of damages in forests was also studied. Those factors were, among others, species composition of the forest stand, canopy architecture, height and breast height diameter (Peltola et al. 2000; Wilson & Oliver 2000) as well as characteristics of biotope, of which the most important are elevation angle and exposure (Peterson & Pickett 1990). A complex analysis of diverse factors influencing the extent and distribution of injuries was presented in numerous scientific papers (Mayer 1989; Peterson 2000; Whigham et al. 1999; Ni Dhubhain et al. 2001) and special publications (e.g. Coutts & Grace, eds 1995). Among the whole set of possible causes, Zajączkowski (1991) as well as Kellomäki & Peltola (1999) point at the site location in the vicinity of forest as a main factor influencing the spatial distribution and extent of damages in forest stands. Also Hassinen et al. (1998), Campbell (1997), Ruel et al. (1998) as well as Gardiner et al. (2000) drew attention to the significant influence of this factor on the extent of damages in forests. Also in our study, we have concluded that more severe damages occur closer to a fringe of forest. A similar relationship was described by Laurance et al. (1998) for forests of the tropical zone.

Besides the field-forest boundary, the edge effect can occur also at felling sites located inside forest complexes. At the study site Komorza, the extent of losses was probably increased by the presence of the traffic route cutting through the forest complex. Influence of this landscape element on the occurrence of wind-induced damages in forests was ascertained by Ruel (2000).

The spatial distribution of wind damages in the Tuchola Forest was also affected by the land use history. Since the fertility of soils depends on how the land was used in the past. In the region of the Tuchola Forest many secondary forests occur today on poor, formerly arable, sandy soils, such as dry or ericaceous pine forest. Such forests occupy rather small areas among lands constantly covered with forests. The NDVI of such secondary forests is most often low as compared with the forests growing around them. The green biomass of secondary forests is smaller than e.g. biomass of assimilation apparatus of fresh pine forests dominating on permanently afforested soils. Different relations occur in forests neighbouring with large agricultural areas. In such places, relatively fertile are also formerly arable soils, where forest was reconstructed and secondary forests are most often directly contiguous to fields or meadows. With this kind of landscape structure, green biomass of secondary forests is higher than of pine forest stands growing on forest soils in the habitat of fresh pine forest, therefore their NDVI also reaches a high value. In such conditions, perhaps, a high content of chemical elements, occurring in formerly arable soils and increasing the growth rate of forest stand, causes that above-ground biomass of trees is high, and consequently the proportion between above-ground and underground parts is disturbed. The root system does not withstand the high load and with stronger wind gusts, root or stem breakages follow. Low resistance to the wind activity can be intensified by the activity of fungi, with which trunk tissues display reduced hardness and elasticity. Influence of parasitic fungi on the reduction of wholesomeness and the quality of timber of forest stands growing on formerly arable soils, and at the same time on the increase of their susceptibility to stem and root breakages generated by wind, was indicated by Rykowski & Sierota (1983).

The above presented relations occur at the study site Wielka Komorza, where analysed forests neighbour with vast and fertile agricultural areas. Perhaps such complex of abiotic and biotic factors contributed to the fact that at the field-forest boundary in the Forest District Komorza, wind damages were the most severe.

For the spatial analysis of root and stem breakages, methods of satellite remote sensing were applied, which are nowadays one of the most important tools for monitoring the forest condition (Kennedy ed. 1997). The satellite image Landsat 7ETM+, applied in this work, proved its usefulness in recognizing forests growing on poorer soils or more fertile than soils in typical fresh pine forests dominating on permanently afforested soils. Field resolution of this satellite's scanner also enables identification of larger areas of wind-fallen forest. For localization of smaller areas and root or stem breakages, a higher resolution is required. Franklin et al. (2001) studied changes within the canopy resulted from falling out of single trees, by applying images of 4 m resolution. Thus, this condition can be fulfilled by images of the satellite Ikonos, which recently are more and more often applied in the analysis of changes of the vegetation cover structure (Tanaka & Sugimura 2001; Aster et al. 2002; Oudemans et al. 2002). The usefulness of images from the satellite Ikonos for the analysis of changes in the forest canopy resulting from falling out of single trees from the upper forest layer as a result of wind activity, was confirmed also in the present research.

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References

Aster G. P., Palace M., Keller M., Pereira R., Jr., Silva J. N. M. & Zweede J. C., 2002, Estimating canopy structure in an Amazon forest from laser range finder and IKONOS satellite observations, Biotropica 34(4): 483–492.

Atlas Rzeczypospolitej Polskiej [Atlas of the Republic of Poland], 1993–1997, Główny Geodeta Kraju, [Chief Geodesist of a Country], Warszawa.

Boinski M., 1999, Podstawy geobotanicznej delimitacji Rezerwatu Biosfery „Bory Tucholskie", [w:] A. Barcikowski, M. Boinski, A. Nienartowicz (eds), Wielofunkcyjna rola lasu. Ochrona przyrody – Gospodarka – Edukacja [Basis of geobotanical delimitation of the Bory Tucholskie Biosphere Reserve, [in:] Multifunctional Role of a Forest. Nature Protection – Economy – Education] O.W. "Turpress", Toruń: 19–40.

Boinski M., 2002, Roślinność leśna Tucholskiego Parku Krajobrazowego, [w:] M. Ławrynowicz & B. Rózga (eds.), Tucholski Park Krajobrazowy 1985–2000. Stan wiedzy [Forest vegetation of the Tucholski Landscape Park, [in:] Tucholski Landscape Park 1985–2000. State of knowledge], Wyd. Uniwersytetu Łódzkiego, Łódź: 245–355.

Braun S., Schindler Ch., Volz R. & Flückiger W., 2003, Forest damages by the storm 'Lothar' in permanent observation plots in Switzerland: The significance of soil acidification and nitrogen deposition, Water, Air and Soil Pollution 142: 327–340.

Campbell D. J., 1998, Salt-wind induced wave regeneration in coastal pine forests in New Zealand, Can. J. For. Res. 28: 953–960.

Clarke R., 2001, Lothar and Martin, WMO Bulletin 50: 54–59.

Coutts M. P. & Grace J. (eds), 1995, Wind and Trees, Cambridge University Press, Cambridge.

Foster D. R. & Goose E. R., 1992, Patterns of forest damage resulting from catastrophic wind in central New England, USA, J. Ecol. 80: 79–98.

Franklin S. E., Wulder M. A. & Gerylo G. R., 2001, Texture analysis of IKONOS panchromatic data for Douglas-fir forest age class separability in British Columbia, Int. J. Remote Sens. 22: 2627–2632.

Gardinner B., Peltola H. & Kellomäki S., 2000, Comparison of two models for predicting the critical wind speeds required to damage coniferous trees, Ecological Modelling 129: 1–23.

Gorzelak A. (ed.), 1999, Zalesianie terenów porolnych [Afforestation of postagricultural lands], Instytut Badawczy Leśnictwa, Warszawa.

Hassinen A., Lemettinen M., Peltola H., Kellomäki S. & Gardiner B., 1998, A prism-based system for monitoring the swaying of trees under wind loading, Agricultural and Forest Meteorology 90: 187–194.

Kellomäki S. & Peltola H., 1999, Silvicultural strategie in forest management to optimize yield and growth in boreal forests while minimizing the risks of wind and snow damage, [in:] C. A. Brebbia & J. L. Usó (eds), Ecosystems and Sustainable Development, Advances in Ecological Sciences, Vol. 2, WIT Press, Joensuu: 285–303.

Kennedy P. (ed.), 1997, Application of Remote Sensing in European Forest Monitoring, European Comission, Luxembourg.

Kondracki J., 1978, Geografia fizyczna Polski [Physical geography of Poland], PWN, Warszawa.

Kunz M., Nienartowicz A. & Deptuła M., 2000, The use of satellite remote sensing imagery for detection of secondary forests on post-agricultural soils: A case study of Tuchola Forest, Northern Poland, [in:] J. L. Casanova (ed.), Remote Sensing in the 21st Century. Economic and Environmental Applications, Proceedings of the 19th EARSeL Symposium, Valladoid, Spain, 31 May–2 June 1999, A. A. Balkema, Rotterdam–Blookfield–2000: 61–66.

Laurance W. F., Ferreira L. V., Rankin de-Merona J. M. & Laurance S. G., 1998, Rain forest fragmentation and the dynamics of Amazonian tree communities, Ecology 79(6): 2032–2040.

Lekes V. & Dandul I., 2000, Using airflow modeling and spatial analysis for defining wind damage risk classification (WINDARC), Forest Ecology and Management 135: 331–344.

Mayer H., 1989, Windthrow, Phil. Trans. R. Soc. Lond, B 324: 267–281.

Mayer H. & Schindler D., 2002. Forstmeteorologische Grundlagen zur Auslösung von Sturmschäden im Wald in Zusammenhang mit dem Orkan "Lothar" [Forest meteorological fundamentals of storm damages in forests in connection with the extreme storm "Lothar"], Allg. Forst-u. J.-Ztg. 173(11–12): 200–208.

Mitchell S. J., Hailemariam T. & Kulis Y., 2001, Empirical modeling of cutblock edge windthrow risk on Vancouver Island, Canad, using stand level information, Forest Ecology and Management 154: 117–130.

Ni Dhubhain A., Walshe J., Bulfin M., Keane M. & Mills P., 2001, The initial development of a windthrow risk model for Sitka spruce in Ireland, Forestry 74(2): 161–170.

Nienartowicz A., Kunz M., Domin D. & Deptuła M., 2002, Ecological consequences of changes in landscape structure in the neighbourhood of Brusy in 19th and 20th century, Ecological Questions 1: 117–135.

Oudemans P. V., Pozdnyakova L., Hughes M. G. & Rahman F., 2002, GIS and Remote Sensing for detecting yield loss in cranberry culture, Journal of Nematology 34(3): 207–212.

Pearce R., Lloyd D. & McConnell D., 2001, The post-Christmas 'French' storms of 1999, Weather 56: 81–91.

Peltola H., Kellomäki S., Hassinen A. & Granander M., 2000. Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland, Forest Ecology and Management 135: 143–153.

Peterson Ch. J., 2000, Catastrophic wind damage to North American forests and the potential impact of climate change, The Science of the Total Environment 262: 287–311.

Peterson Ch. J. & Pickett S. T. A., 1990, Microsite and elevational influences on early forest regeneration after catastrophic windthrow, J. Veg. Sci. 1: 657–662.

Quine C. P. & Bell P. D., 1998, Monitoring of windthrow occurrence and progression in spruce forests in Britain, Forestry 71(2): 87–97.

Quine C. P., Humphrey J. W. & Ferris R., 1999, Should the wind disturbance patterns observed in natural forests be mimicked in planted forest in the British uplands?, Forestry 72(4): 337–358.

Ruel J.-C., 2000, Factors influencing windthrow in balsam fir forests: from landscape studies to individual tree studies, Forest Ecology and Management 135: 169–178.

Ruel J.-C., Pin D. & Cooper K., 1998, Effect of topography on wind behaviour in a complex terrain. Forestry 71(3): 261–265.

Rykowski K. & Sierota Z., 1983, Wpływ huby korzeni w drzewostanie na gruncie porolnym na powstawanie wiatrowałów w 1981 r. [Influence of Fomes annoscus root and butt rot in a stand on post-agricultural land on the incidence of windfall in 1981], Sylwan 1983, 12: 59–70.

Schelhaas M.-J., Nabuurs G.-J. & Schuck A., 2003, Natural disturbances In the European forests in the 19th and 20th centuries, Global Change Biology 9: 1620–1633.

Tanaka S. & Sugimura T., 2001, A new frontier of remote sensing from IKONOS images, Int. J. Remote Sensing 22: 1–5.

Trampler T., Kliczkowska A., Dmyterko E. & Sierpińska A. (eds), 1990, Regionalizacja przyrodniczo-leśna na podstawach ekologiczno-fizjograficznych [Ecological and physiographical basis of natural – forest regionalisation], PWRiL, Warszawa.

Ulbrich U., Fink A. H., Klawa M. & Pinto J. G., 2001, Three extreme storms over Europe in December 1999, Weather 56: 70–80.

Whigham D. F., Dickinson M. B. & Brokaw N. V. L., 1999, Background canopy gap and catastrophic wind disturbances in tropical forests, [in:] L. R. Walker, Ecosystems of the World, 16. Ecosystems of Disturbed Ground. Elsevier, Amsterdam–Lausanne–New York–Oxford–Shannon–Singapore–Tokyo: 223–252.

Wesp U., 2000. Die Wahrheit über Lothar (die Weihnachtsorkan 1999), http://www.de-badner.de/lothar.htm

Wilson J. S. & Oliver C.D., 2000, Stability and density management in Douglas-fir plantations, Can. J. For. Res. 30: 910–920.

Wright J. A. & Quine C. P., 1993, The use of a geographical information system to investigate storm damage to trees at Wykeham forest North Yorkshire, Scot. For. 47(4): 166–174.

Zajączkowski J., 1991, Odporność lasu na szkodliwe działanie wiatru i śniegu [The Resistance of a Forest on Destructive Influence of Wind and Snow], Wydawnictwo Świat, Warszawa.