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Spatial distribution and extent of damages caused by wind storms in tree stands of the Tuchola Forest

Grzegorz Koziński, Andrzej Nienartowicz

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

1. INTRODUCTION

In the 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. At the end of 1999, the highest losses in tree-stands that resulted from this ecological factor took place in the northern part of the aforementioned region. They related to the hurricane impact that descended upon Western and Central Europe on 26 December 1999. That hurricane, referred to as the „Lothar" in meteorological and ecological literature (Wesp 2000, Clarke 2001, Pearce et al. 2001, Ulbrich et al. 2001, Mayer and Schindler 2002, Braun et al. 2003), had brought about considerable forests damages mainly in Germany, France, Switzerland and Austria. In the Tuchola Forest, the most severe damages to forest ecosystems from that hurricane were recorded in the Przymuszewo Forest Inspectorate. Those were single tree stem and root breakages. No surface damages were noted.

Six months later, i.e. on 22 June 2000, the second large hurricane affected the Tuchola Forest. It brought about surface root and stem breakages. This type of damages occurred mainly in Forest Inspectorates of Czersk and Woziwoda, which are subordinate of the Toruń RDLP (Regional Directorate of the "State Forests" Holding).

It follows from preliminary analysis of spatial distribution of the damages that the location of root and stem breakages corresponds to distribution of the secondary forests, i.e. those reconstructed on formerly arable lands which were in agricultural use in the recent past. According to Gorzelak (1999), the destructive activity of wind in forests on formerly arable lands is enhanced by poorly developed tree root system and pathogen-related weakening of the root integrity. Also, the close vicinity of non-forested areas, i.e. the larger areas of agricultural fields, meadows and pastures, as well as the bigger mid-forest lakes, could have some influence on the type and extent of wind-induced injuries.

The aim of the present work is to verify the above hypotheses by field survey at the following three study sites: 1 – in the vicinity of the locality of Komorza Wielka, in the Woziwoda Forest Inspectorate; 2 – in the Bory Tucholskie National Park; 3 – in the valleys of the Trzemeszno Lake and the Brda River, in the Okręglik Forest District, the

Czersk Forest Inspectorate. Stem and root breakages occurred there mainly nearby the field-forest boundary, as well as in the vicinity of big lakes, and also within fragments of the forest areas, of which the secondary forests reconstructed on formerly arable lands form a considerable part. To analyse the distribution of wind-induced damages, the stock-taking data on wind-fallen trees and logged timber was used, as well as data from the old and contemporary cartographic materials, and the measurements taken with the GPS receiver, and also the satellite remote sensing and modelling methods for ecological phenomena with use of the GIS technology were applied there.

2. THE STUDY AREA

2.1. General characteristic of the Tuchola Forest

The Tuchola Forest is situated in northern Poland and forms one of the Pomeranian sub-regions (Kondracki 1978, Atlas Rzeczypospolitej Polskiej/Atlas of the Republic of Poland 1993–1997). It is a vast area located westwards of the Lower Vistula River, within the Brda and Wda rivers catchment areas. This sub-region occupies ca. 5 000 km^2 area. A vast outwash plain at the foreland of terminal moraines originated from the Pomeranian stage of the last Baltic glaciation is a geo-morphological form predominating there. The surface of the outwash plain is cut through by postglacial gullies, which are filled with numerous lakes and rivers. Low-fertile soils developed mainly from poor sands dominate there. Fresh and dry pine forests constitute the major vegetation formation there. According to Boinski (2002), they are syntaxonomically classified among *Leucobryo-Pinetum*, *Peucedano-Pinetum* and *Cladonio-Pinetum* associations. Some 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 share in tree-stands, also in poorer habitats where nowadays Scots pine strongly predominates. Oak-hornbeam forests, oak and beech forests covered the areas larger than nowadays, but the anthropopressure which lasted for several centuries had caused their transformation into agricultural lands and heathlands, or replacement by pine monocultures. The most significant changes in nature of the forest stands followed on the turn of the 19th Century when the Prussian forestry authorities 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 in the forest area followed after 1920 when most of the Tuchola Forest region was integrated into territory of the reborn Polish State. The subsequent afforestation period of the formerly arable lands and waste lands followed after World War II when, in course of the so called land reform, the large private estates were partially parcelled out and donated to individual farmers, and in part included also into the State-owned forests, and the afforested, mainly with pine species. Afforestation of formerly arable lands takes place also nowadays, as the unprofitableness of farming managed by the Forest Inspectorates staff on small mid-forest plots leased from the State-owned forests caused that their tenants ceased the cul-

tivation. Usually, although it is not any rule, after several years of laying fallow those areas undergo afforestation (Kunz et al. 2000, Nienartowicz et al. 2002).

At present, the forestage of the Tuchola Forest sub-region accounts for about 50%, of which the pine forest stands are absolute majority (Boinski 1999). They developed from artificial regeneration, mainly planting, on poor sandy soils, not suitable for cultivation. They mostly fall within the middle age classes. Small area is occupied by tree-stands older than 100 years.

Deciduous forests fall within syntaxa *Tilio-Carpinetum*, *Galio-Carpinetum*, *Stellario-Carpinetum*, *Aceri-Tilietum*, *Calamagrostio-Quercetum petraeae*, *Luzulo pilosae-Alnetum* and occur in the valleys, mainly of the Brda and Wda rivers, as well as their tributaries, where also birch forests ***Betuletum pubescentis***, elm forests *Ficario-Ulmetum*, and alder forests *Ribo nigri-Alnetum*, *Circaeo-Alnetum*, *Poo trivialis-Alnetum*, *Stellario-Alnetum* occur. Many deciduous forests are under legal reserve protection. In the uplands, besides fresh and dry pine forests, degradation forms of deciduous forests occur, as caused by introduction of pine into the more fertile habitats. Those are so-called pine coppices, predominated in the herb layer by the following species: *Arrhenatherum elatius*, *Agrostis vulgaris*, *Deschampsia flexuosa*, *Pteridium aquilinum* (Boinski 2002).

To recapitulate, it is noteworthy that the present-day condition of forests in this region has been influenced, to a large extent, by three processes: 1 – displacement of forest into the most poor habitats, 2 – impoverishment of species diversity of tree-stands as a result of routine forestry, 3 – afforestation of deforested areas 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 the wind caused damages in the Tuchola Forest. The first level consisted the whole region and the Forest Inspectorate was the basic unit for overall analysis of damages. The second level consisted of small areas where, however, the wind-induced damages in tree-stands were the highest throughout the region as the whole. Those areas were selected upon results obtained from analysis carried out at the first level. The territories selected 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. Forest Subdivision was the basic unit for detailed analyses conducted at the second level.

2.2.1. General studies

The operational regions of 22 Forest Inspectorates formed the research area at the first level that are at least partly included into the nature-forest province of the Tuchola Forest, according to Trampler et al. (1990). As regards their organizational structure, they are subordinates 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 area of the Bory Tucholskie National Park. In order to compare the extent of damages, observations were also carried out in the Forest Inspectorates neighbouring to the Tuchola Forest Province, especially on its south-eastern side, i.e. in the area of the Toruń RDLP.

2.2.2. Detailed studies

Three sites were selected for detailed studies. The first site consisted of marginal fragments of forests alongside their boundary demarking cultivation fields and meadows in the Komorza Forest District (the Woziwoda Forest Inspectorate). The forest fragment surveyed in relation to spatial distribution of wind-induced damages is situated in the buffer zone of the Tuchola Landscape Park. It is located north-eastwards of the town of Tuchola on both sides of No. 237 National Road. The forest adjoins to vast agricultural area.

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

The second site consists of the Bory Tucholskie National Park, as situated on the eastern side of the Charzykowskie Lake. This water body is one the biggest lakes in Poland. Another big water reservoir, the Karsińskie Lake, is located at the vicinity of its northern part. In the Park area occupying 4 798.23 ha, the forest communities strongly predominate (83%) in terrain cover structure. Water reservoirs rank as the second on this list and account for 11% of the Park area. It follows from the analysis of historical cartographic maps that in the past, the National Park area was mostly afforested. Minor deforestation events, being 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 Seven Lakes Stream). In the area considered, forest fellings were reduced already before establishment of the National Park. For this reason, in the present-day structure of the forest stands, the higher age classes take a significant share. Scots pine absolutely predominates among tree species. The oldest and most robust pine forest stands occur in the central part of the National Park in the vicinity of the Gacno Małe and Gacno Wielkie lakes, and on the western side of the Ostrowite Lake. Pine forest stands overgrow there quite a distinct terrain elevations.

The third study site is located within the thick forest complex in the area of the Okręglik Forest District in the Czersk Forest Inspectorate. The study area is located southwards of the Bory Tucholskie National Park and eastwards of the Chojnice – Brusy – Kościerzyna highway. Observations covered two sites. The first one includes forests located within the lake gully constituting a natural extension of the Dybrzk, Kosobudno, and Trzemeszno lake series. The second site under detailed analyses was a fairly large valley of the Brda River running across the Kosobudno Lake. In the lake gully and the river valley, likewise in the uplands, fresh pine forests dominate, with forest stands mostly within the average age classes. Terrain depressions situated at water reservoirs are overgrown by 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. Then, the sheets of scale 1:25,000 topographic maps, were scanned and fitted in by means of the MicroStation 95 software with the Descartes overlay. Those maps were overlaid in the process of geometric rectification with updated scale 1:20,000 forest management map, as well as 19th Century and early 20th Century historical topographic and forest management maps. Most of information on the past land cover and land use was provided by the Schrötter-Engelhardt map produced in the turn of the 18th Century, as well as the forest management map of the Prussian Königlichen Oberförsterei Chotzenmühl, dated 1896. Also the Landsat 7 ETM+ a satellite image dated May 2000 was fitted into the system of coordinates as a raster information layer.

In order to determine spatial distribution of the secondary forests on formerly arable lands and the sites where forest was continuously present during the recent several Centuries, a map of spatial variation NDVI was produced on the basis of the satellite image, as a separate information layer. The values of NDVI were calculated by 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 Thematic Mapper scanner for channel 3 (RED, 630–690 nm) and channel 4 (IR, 760–900 nm). In order to calculate NDVI and generate spatial diversification maps of this index, the IDRISI software was applied.

By application of the GIS technology, spatial relations were determined between distribution of colours used on NDVI spatial variation map and the location of the secondary post-agricultural forests on contemporary and historical topographic maps and forest management maps.

On the raster layers prepared, after × 1000 rescaling, the current forest districts and sub-districts were digitalized with use of the ArcView 3.2 ESRI software. The distribution of wind-induced damages in the study area was charted by means of the GPS receiver (Smart Antenna with the software Termap). The location coordinates of root and stem breakages were imported into the project by means of the XYZ module in the MicroStation J/Polish software. In 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 of 1998–2002 coming from the "State Forests" Holding Information System, as provided by the Forest Inspectorates, in the area where detailed studies were conducted. Information on distribution of wind-induced damages and the timber amount removed was also acquired from Management of the Bory Tucholskie National Park. The database included the forest address information (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 afforestation rate, name of the main canopy species, its age and the quantitative share.

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

With use of tables produced by this software, data was 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 the area surface of a given forest subsection. The extents of the injuries calculated were then summed up separately for each buffer zone. By application of the table comprising 2 vectors of numbers, i.e. the volume of logged timber in m^3 per ha and the distance of each 86 buffer zones from the field-forest boundary in meters, a correlation coefficient was calculated, as well as a function expressing relation between those parameters was defined. The Statistica and Curve-Expert software packages were applied to perform calculations.

The analysis of relationships between the damage extent and the habitat type and tree species in the canopy was also performed with use of information on each forest subdivision for the Komorza site and with application of the „combined subjects" method.

In case of the Bory Tucholskie National Park study polygon, the distribution of root throws and stem breakages, as determined by means of the GPS receiver, was plotted upon the digital map of this natural object. Then, the satellite Ikonos image, as dated August 2003, was superimposed upon this information layer. The satellite image was performed with 4 m field resolution in the multi-spectral 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 standardised NDVI vegetation index. Also comparisons were made between mosaicness of the tree canopy image from the National Park and the area situated outside the Park, on the western side of the Charzykowskie Lake, where wind damages during the considered period were small.

For Site 3, i.e. the Okręglik Forest District, a digital terrain model was drawn up. The positions of both stem and root breakages of single trees according to GPS readings, and also of the observed surface damages were plotted upon the three-dimensional image of this terrain. The relations were evaluated there between the occurrence of

wind-induced disturbance in the canopy structure and the location of the major relief elements, especially the route of river valleys and the lake gullies.

Data on distribution and extent of damages in the areas located outside the three study polygons, selected for detailed analyses, was obtained through circulation of questionnaires among individual Forest Inspectorates. Where appropriate, the information obtained was defined accurately through both the website connection and the direct contacts with the Forest Inspectorates staff.

4. RESULTS

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

It was ascertained upon data supplied by the Forest Inspectorates that in the period of 1998–2002, logging of timber from stem and root breakages amounted to 602,000 m^3. Out of this amount, 57.8% accounted for timber removed in 2000. Such intensive logging of timber in 2000 was brought about by damages induced by two hurricanes, i.e. the „Lothar" on 26 December 1999, and removed in the early part of 2000, as well as damages being the post-effects of the 22 June 2000 wind-storm, and removed later in 2000.

In total, the 2000 logging of timber from root and stem breakages in the Forest Inspectorates subordinate to the Tuchola Forest nature-forest district amounted to 347,931.74 m^3. That amount includes 109,720.56 m^3 logged in RDLP Toruń, Gdańsk 81,586.66 m^3 in DLP, and 156,624.52 m^3 in RDLP Szczecinek (Table 1).

During the entire 5-year period analysed, the least logging of timber from wind damages was done in 1998. It accounted for 3.59% of the total 2000 logging. Quite a lot of timber from wind damages was acquired in 2002. The sum calculated for this year accounts for 49.73% of the timber volume acquired in 2000.

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

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
S	193,438.01	156,898.45	251,578.77	6,010,915.33

*including the Bory Tucholskie National Park

The highest logging of timber from wind damages in 2000, amounting to 52,000 m^3, was recorded in the Bytów Forest Inspectorate. The volumes significantly exceeding the average volume of 16,000 m^3 were also recorded in the Lipusz, Miastko and Szczecinek Forest Inspectorates. Those were 32.33 and 37.5 thousands m^3 wood, respectively. The amounts of wood above the annual average were acquired also in the Rytel and Czersk Forest Inspectorates, that amounted to 29 and 23 thousands m^3 timber. The quantity of timber, closest to an average volume, was acquired from root and stem breakages in the Woziwoda and Przymuszewo Forest Inspectorates, amounting to 13 and 18 thousands m^3 wood, respectively.

It follows from the above data that two out of the three research polygons, analysed in detail, are situated within or in the vicinity of the "State Forests" Holding economic entities where damages caused by destructive wind force were mostly similar to the average values. In Rytel Forest Inspectorate, which in the past included a part of the Bory Tucholskie National Park area, logging of wood from root and stem breakages was clearly higher than the average value per single Forest Inspectorate.

Changes in the amount of wood acquired in 1998–2002 by particular Forest Inspectorates are presented in Figure 1.

The histograms presented in Fig. 1 and also the values quoted in Table 1 both 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 Inspecto-

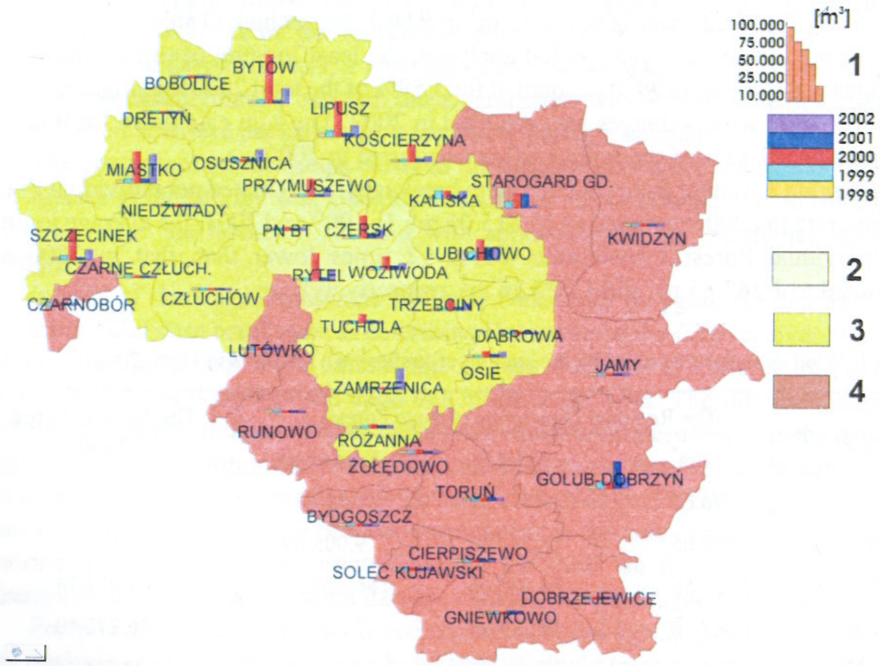

Fig. 1. The distribution and extent of wind damages measured by the volume of timber logged in the Tuchola Forest and its neighbouring areas in 1998 – 2002; 1 – timber logging in m^3/year in the subsequent years, 2 – selected Forest Inspectorates with polygons for detailed studies, 3 – other Forest Inspectorates within the Tuchola Forest, 4 – other Forest Inspectorates outside the Tuchola Forest

rates of the Szczecinek RDLP accounted for 45.02% of the total damages. The remaining proportion nearly 55% included timber removed in 14 Forest Inspectorates subordinate to the Gdańsk and Toruń RDLPs. It was 23.45% and 31.53%, respectively, of timber logged from root and stem breakages in the whole territory of the Tuchola Forest in 2000.

4.2. The influence of the field-forest boundary and the past management on spatial distribution of damages

The total area of forest subsections as included in the study site of the Komorza Forest District is 1 682.62 ha. Based upon analysis of data acquired form historical forest stocktaking, old topographic maps and forest economic maps, as well as the 2000 satellite image, it was found that the secondary post-agricultural forests covered 833.85 ha area, accounting for 50.77 % of the study area total. Forests on soils being not used for agricultural purpose in the past covered 808.6 ha, that accounts for 49.23 %. They were located in the heart of the forest complex. The secondary forests occurred next to the field-forest border (Figure 2).

Three surface damages of 0.23 ha, 0.44 ha, and 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 acquired from those

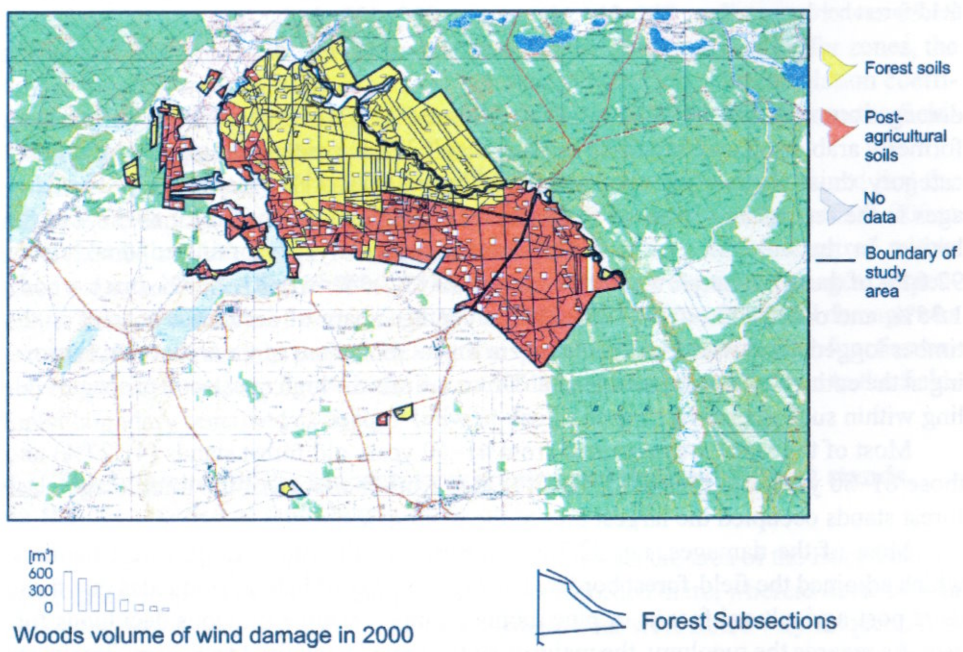

Fig. 2. Spatial distribution of the secondary forests on the formerly arable lands and on forest soil, structuring of the study area into the forest subsections and the volume of timber acquired from stem breakages in particular subsections. 1 – volume of fallen wood, 2 – boundaries of the study area,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

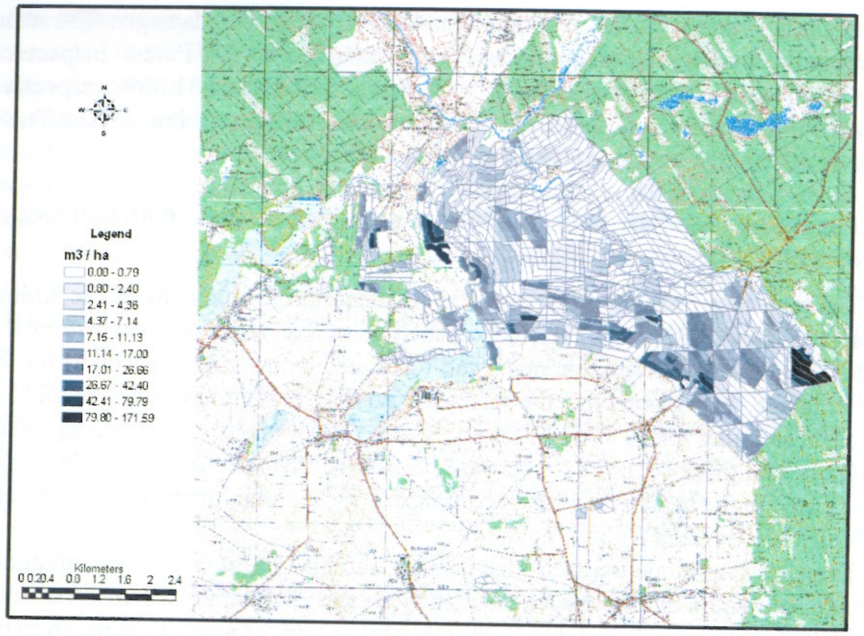

Fig. 3. The volume of timber logged in successive buffer zones arranged into 100 m intervals from the field-forest border

damages amounted to 4 478.62 m^3. Out of this, 3 831.73 m^3 was acquired in forests on formerly arable soil and 646.89 m^3 on forest soil. When recalculating per ha of a forest category, those figures amounted to 4.59 m^3/ha and 0.80 m^3/ha, respectively. The damages in the secondary forests on the formerly arable land accounted for 84.37% of the losses. In the volume acquired, pinewood significantly predominated, 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 timber logged was lower than their share in the total biomass of the forest stands growing at the entire Komorza research area. This confirms the high resistance of species falling within such genera like beech or oak to wind impact.

Most of the wood was acquired from 41–60 years old forest stands (41.27%) and those 61–80 years old (27.51%). This resulted from the fact that the middle-age class forest stands 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. The high fertility of habitats indicates that those were post-agricultural forests or pine monocultures replacing previous deciduous forests. As regards the typology, the majority of timber was acquired from stem breakages in fresh mixed coniferous forest habitats (46.73%), fresh coniferous forest (26.60%) and fresh mixed forest (24.58%).

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

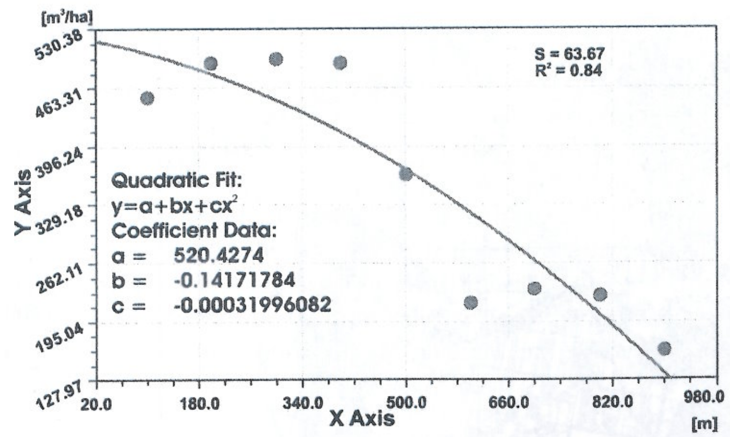

Fig. 4. Function expressing relationship between the volume of timber logged and the distance to the field-forest border at 100 m intervals. Axis X – distance to the field-forest border, axis Y – volume of timber logged in m^3/ha

By way of the analysis carried out at 100 m intervals, it was ascertained that the most severe damages occurred within 0–100 m zone (373.49 m^3/ha), then at 200–300 m zone (264.06 m3/ha) and in 100–200 m zone (212.71m^3/ha). Wood acquired within these zones accounted for 33.98%, 24.02% and 19.35% of the total damages, respectively. In total, within the forest zone at 300 m distance, 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 their distance to the field-forest boundary remained as in Fig. 4.

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

This relationship was studied at Site 2 which consists the area of the Bory Tucholskie National Park. The surface damages were not recorded there, whereas devastations in form of root throws and stem breakages of single trees were noted very frequently. A part of the National Park on the southern side of the Struga Siedmiu Jezior (the Seven Lakes Stream), in the vicinity of Lakes Gacno Małe and Gacno Wielkie (Fig. 5) was the major site of their occurrence. That part of the Park is overgrown by the oldest forest stands, whereas no occurrence of the secondary reconstructed forests was found on soils temporary used for agricultural purpose. On the map of spatial diversification of

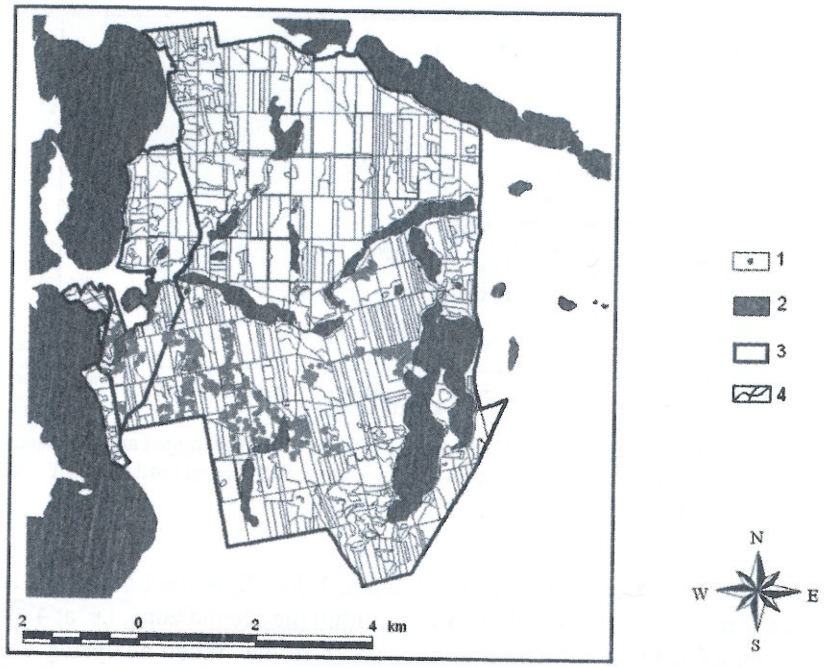

Fig. 5. Wind damages in the Bory Tucholskie National Park. 1 – location of the root and stem breakages, 2 – lakes, 3 – the National Park border, 4 – borders of forest subsections

the NDVI index for the National Park area, as drawn up with the Ikonos satellite data, the heterogeneity of vegetation cover is the highest on the sites where the wind damages are mostly 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 against tree stands undisturbed by the wind factor, as located on the western side of the Charzykowskie Lake.

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

It follows from spatial distribution of damages caused by strong winds and presented on numerical map of the Bory Tucholskie National Park (Fig. 5) that the root throws and stem breakages occurred more seldom northwards of the Struga Siedmiu Jezior (the Seven Lakes Steam) than on its southern side. Such differences in the damage distribution occurred despite the fact that westwards of both the southern and northern part of the Park, there are big lakes situated in a close proximity: the Charzykowskie Lake (in the southern part of the Park) and the Karsińskie Lake (in its northern part).

4.4. The influence of field relief on spatial distribution of damages

At Site 3, i.e. in the area of the Okręglik Forest District in the Czersk Forest Inspectorate, where the influence of terrain orography on the occurrence and extent of wind-induced damages was studied, 10 surface root breakages were recorded (Fig. 6). It follows from digital model of the terrain that those areas occur mainly in the vicinity of valleys alongside the extension of the Trzemeszno Lake gully. However, they do not take up the areas situated at the lowest altitude. In their location, the influence of generally dominating western winds has been revealed, rather than the shifting likelihood of fast-moving air masses alongside the lake valleys, since the most of the surface root throws have been located alongside the nearly straight line east-westwards of the eastern part of the Trzemeszno Lake.

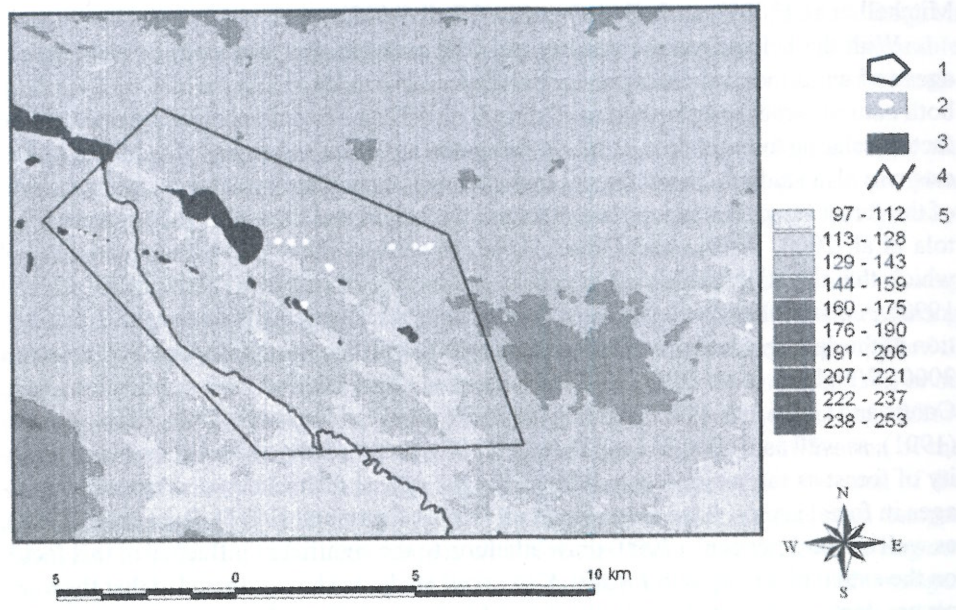

Fig. 6. The digital elevation model and surface deforestation in the Okręglik Forest District, 1 – the zone with potential occurrence of wind damages, 2 – the surface damages, 3 - lakes, 4 – rivers, 5 – the altitude [m] above sea level

5. DISCUSSION AND CONCLUSIONS

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

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

With the help of remote sensing and GIS methods, the frequency of stem breakages and wind-induced damages were compared in forests of diverse history, including both natural forest and plantations (Quine et al. 1999). The influence of several diverse factors relating to vegetation cover on the spatial structure and extent of damages to forests was also studied. Those factors included, amongst others, the species composition of the forest stand, the canopy architecture, the height and breast height diameter (Peltola et al. 2000, Wilson and Oliver 2000), as well as the biotope characteristics, of which the elevation angle and exposure are mostly important (Peterson and Pickett 1990). A comprehensive analysis of diverse factors influencing the extent and distribution of the damages 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 and Grace, eds 1995). Among the entire set of the causes possible, Zajączkowski (1991), as well as Kellomäki and Peltola (1999), point out the site location in the vicinity of forest as the major 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) draw attention to the significant influence of this factor on the extent of damages to forests. Also in our study, we have concluded that the more severe damages occur closer to the forest fringe. A similar relationship was described by Laurance et al. (1998) for tropical zone forests.

Besides the field-forest boundary, the edge effect may appear also at the felling sites located inside forest complexes. At the Komorza study site, the extent of losses was likely expanded by the presence of the traffic route running across the forest complex. The 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 soil fertility depends on the land-use methods applied in the past. In the Tuchola Forest region, many secondary forests, such as dry or ericaceous pine ones, occur today on poor, formerly arable, sandy soil. Such forests occupy rather small areas among lands constantly covered with forests. The NDVI of such secondary forests is most often low in comparison with the forests surrounding them. The green biomass volume in the secondary forests is smaller than e.g. the biomass of

assimilation apparatus of fresh pine forests dominating on permanently afforested soils. Different relations occur in forests neighbouring the large agricultural areas. On such sites, also formerly arable soils are relatively fertile where the forest was reconstructed and the secondary forests are most often directly contiguous to fields or meadows. With this type of landscape structure, the volume of green biomass in the secondary forests is higher than that in pine forest stands growing on forest soils in fresh pine forest habitats, and therefore their NDVI also reaches a considerable value. Under such conditions, perhaps, a high content of chemical elements, occurring in formerly arable soil and increasing the growth rate of forest stand, causes that the above-ground biomass of trees is high, and consequently, the proportion between the above-ground and underground parts has been disturbed. The root system does not withstand such high load burden and the root or stem breakages follow as induced by the stronger wind gusts. The low resistance to wind impact can be yet intensified by fungal effects, with which the trunk tissues reveal reduction in their hardness and elasticity. The influence of parasitic fungi on reduction of timber integrity and quality in 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 and Sierota (1983).

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

For the spatial analysis of root and stem breakages, the satellite remote sensing methods were applied being nowadays one of the most important tools for monitoring of forest condition (Kennedy ed. 1997). The Landsat 7ETM+ satellite image applied in this work has proved its usefulness in recognizing forests growing on poorer soil or on more fertile ones than in typical fresh pine forests dominating on permanently afforested soil. Field resolution of this satellite's scanner also enables identification of the larger areas of wind-fallen forest. The higher resolution is required for location of the smaller areas and root or stem breakages. By application of 4 m resolution images Franklin et al. (2001) studied the changes within canopy those resulted from falling out of single trees. Thus, this condition can be complied with by the Ikonos satellite images which have been recently the more and more frequently applied in analysis of the changes in the vegetation cover structure (Tanaka and Sugimura 2001, Aster et al. 2002, Oudemans et al. 2002). The usefulness of the Ikonos satellite images for 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 has been confirmed also in the present research.

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