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Application of cartographic sources, satellite imagery Landsat 7ETM+ and GIS technology to spatial analysis of windthrows in Bory Tucholskie Forest

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ABSTRACT: The spatial distribution of wind-induced damages was analysed in the forest complex of Komorza, situated in the Woziwoda Forest Inspectorate, the region of Bory Tucholskie Forest, northern Poland. The discussed damages were caused by a windstorm on the 22nd of June 2000 in the forest fragment neighbouring agricultural grounds. The present study aimed at answering two questions: 1 does closer location of forest in relation to field-forest borderline increase damages in the standing timber? 2 – do wind-induced damages occur more often and are more severe in the secondary forests restored on the formerly arable lands than in the forests, the development of which was not interrupted by temporary agricultural land use after cutting of trees? In order to define changes in forest and farming grounds in the study area, and as well as to identify secondary forests, old and temporary topographic maps were used, forest economic maps and satellite image Landsat 7ETM+ dated year 2000. Information derived from the above sources and also from the forest stock-taking and direct field measurements carried out with application of GPS receiver were organised in the geographic information system. Statistical analysis conducted according to GIS technology with application of computer programs: MicroStation/Bentley, ESRI ArcView3.2 and Idrisi32, proved that factors like the neighbourhood of large non-forested areas and the temporary use of forest soils for farming purposes do indeed increase range and frequency of damages caused by strong wind in the canopy of forest ecosystems.

1 INTRODUCTION

Over the last couple of years in several forest inspectorates of Bory Tucholskie Forest, which is one of the biggest forest complexes in Poland, one can observe an increase of damages caused by the wind. The most serious losses in forest stands resulting from this ecological factor took place in the northern part of the above-mentioned region at the end of 1999. They were related to consequences of the hurricane, which visited Western and Central Europe on the 26th of December. The hurricane, described in 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 damage mainly in forests on the territory of Germany. Losses occurred also in forests of France, Switzerland and Austria. Apart from economic losses also many fatal accidents among people were recorded in all these countries (Ulbrich et al. 2001). The most serious disturbances in forest ecosystems of Bory Tucholskie Forest, resulting from this storm, were recorded in the Forest Inspectorate of Przyuszewo. Those were stem breakages and tree throws.

The second storm took place in Bory Tucholskie Forest half a year later, i.e. 22nd of June 2000. In forest inspectorates of Czersk and Woziwoda the storm brought about surface tree throws and stem breakages, i.e. areas where all trees were blown down.

From the rough analysis of spatial distribution of damages it was evident that the location of tree throws and stem breakages corresponds to the distribution of secondary forests restored on formerly arable lands, which recently were used for farming purposes. According to Gorzelak (1999) in forests on the formerly arable lands destructive activity of wind is enhanced by poorly developed root systems and weakened by pathogens. Also the close vicinity of non-forested areas, i.e. larger areas of agricultural fields, meadows and pastures, and larger mid-forest lakes seemed to have an essential influence on the occurrence of wind-induced disturbances.

The present work aimed at verifying the above hypotheses in the forest inspectorate of Bory Tucholskie, i.e. Woziwoda Forest Inspectorate. Stem breakages and tree throws occurred there in the vicinity of the field-forest borderline, in the forest fragment covered mainly by secondary forest restored on formerly arable lands. When analyzing the distribution of wind-induced damages the stock-taking data of logging and wind-fallen trees, data from old and temporary cartographic materials, and GPS measurements were used, and as well as methods of satellite remote sensing and GIS modeling of ecological phenomena were applied.

2 STUDY AREA

The Bory Tucholskie Forest is situated in northern Poland and constitutes one of the sub-regions of Pomerania (Kondracki 1978, Atlas of the Republic of Poland 1993-1997). It is a vast territory located west of the Lower Vistula, in the catchment area of its two major tributaries – the Brda and the Wda. This subregion covers about 5000 km^2, which makes ca. 1.6% of the whole territory of Poland. The subregion is characterised by immense richness of geomorphologic forms the origin of which is related to the last Baltic glaciation. The vast outwash plain at the foreland of terminal moraines from the Pomeranian stage of the above glaciation period constitutes here the dominating geomorphologic form. The surface of the outwash plain is dissected by post-glacial gullies, which are filled with numerous lakes and rivers.

The predominant vegetation formation on the soils developed mainly from poor sands are fresh and dry pine forests, classified as *Leucobryo-Pinetum, Peucedano-Pinetum* and *Cladonio-Pinetum.* Smaller areas are covered with other types of pine forests: ericaceous pine forest *Calluno-Pinetum*, wet pine forest *Molinio-Pinetum* and marshy pine forest *Vaccinio uliginosi-Pinetum* on organogenic soils. The deciduous species had greater contribution in forest stands in the past. Oak-hornbeam forests, oak forests and beech forests dominated there, but lasting for several centuries anthrop pressure transformed them into agricultural fields and heathlands, or replaced them by pine monocultures. The most serious changes in the forest canopy took place at the turn of the 19th century, when the Prussian forest administration planted the cleared grounds with pine. After 1920, when most of the Bory Tucholskie region was included in the reborn Polish State, also heathlands, fallow lands, degraded pastures and waste lands were afforested. The subsequent afforestation period of formerly arable lands and waste lands followed after the Second World War, when the Polish Communist Government took a decision, within the frame of so-called land reform, to afforest some of the largest estates. Afforestation of formerly arable lands takes place also today, as the non-profitability of farming on small mid-forest plots causes that people taking on lease those fields from state forests resign leaseholds and turn them over for afforestation (Kunz et al. 2000, Nienartowicz et al. 2002).

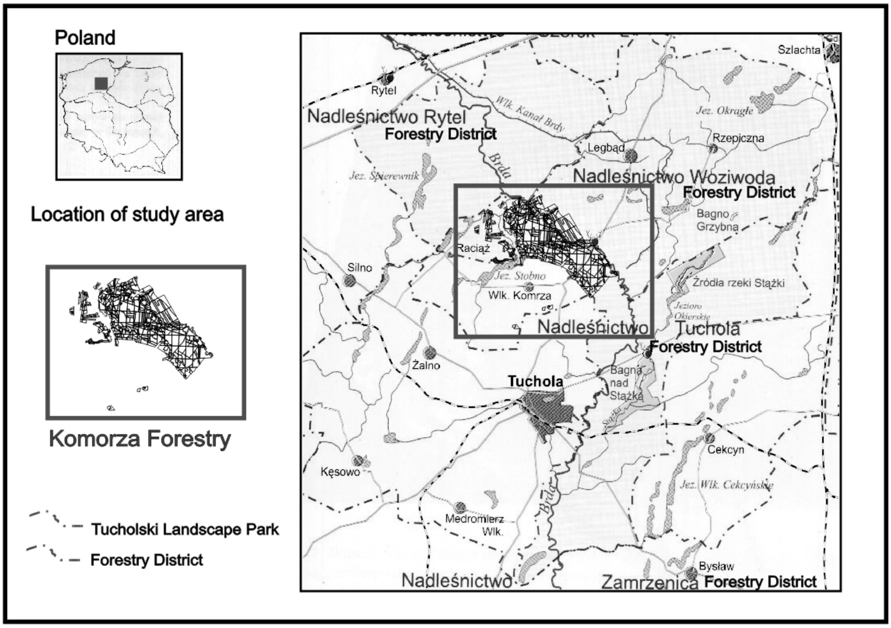

Figure 1. Location of the study area

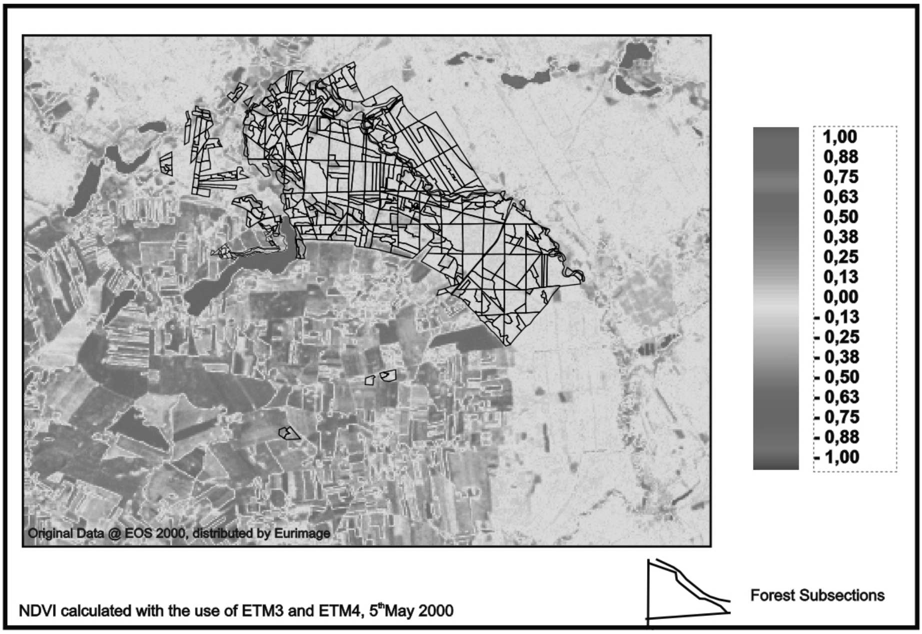

Figure 2. Location and boundaries of the study area in the satellite image Landsat 7 ETM+

At present the forestage of Bory Tucholskie region fluctuates around 50%, of which pine forest stands absolutely dominate over minor populations of deciduous trees (Boinski 1999). Planted pine forest stands grow on poor sandy uncultivable soils. They belong mostly to middle age classes, seldom interspersed with forest stands older than 100 years. Above-mentioned deciduous forests, classified to the following syntaxa: *Tilio-Carpinetum, Galio-Carpinetum, Stellario-Carpinetum, Aceri-Tilietum, Calamagrostio-Quercetum petraeae, Luzulo pilosae-Fagetum*, occur in the river valleys, mainly the Brda and Wda, and their tributaries, where also birch forests *Betuletum pubescentis,* elm forests *Ficario-Ulmetum* and alder forests occur: *Ribo nigri-Alnetum, Circaeo-Alnetum, Poo trivialis-Alnetum, Stellario-Alnetum.* Several deciduous forests, being relics of the remotest ages are under reserve protection. On uplands, besides dry and fresh pine forests, also degradation forms of deciduous forests occur, created by planting of pine on fertile soils. Those are forests dominated by *Pinus sylvestris* in canopy and the following species in undergrowth: *Arrhenatherum elatius, Agrostis vulgaris, Deschampsia flexuosa, Pteridium aquilinum* (Boinski 2002).

Despite considerable transformation, the vegetation cover of Bory Tucholskie Forest still includes numerous floristic and syntaxonomic peculiarities**,** mainly among forest, peat and aquatic (*lobelia*-type lakes) communities**.** In order to protect them, several nature reserves have been created (among them one of the oldest in Europe the Nature Reserve of yew-trees in Wierzchlas, where forest stands are under protection since 1827), one national park and four landscape parks: Wdecki, Wdzydzki, Zaborski and Tucholski.

The forest fragment, studied in respect of spatial distribution of wind-induced damages, is situated in the surrounding of the latter landscape park, i.e. the Tucholski Landscape Park. This forest constitutes the Forest District of Komorza in the Woziwoda Forest Inspectorate. It is located north-east of Tuchola town, along both sides of the national road no 237 from Tuchola to Czersk (Fig. 1). The forest borders upon vast agricultural areas, which until the Second World War belonged to the Wielka Komorza estate, the property of the Polczynski family.

The analysed study area is a forest zone stretching from the field-forest borderline for ca. 2 km inside the forest complex (Fig. 2).

In the north-west the zone circumvents from the village of Raciaz through surroundings of Wielka Komorza village in the eastern part, and towards the neighbourhood of Tuchola town in the south. A considerable part of this zone is covered by secondary forests on formerly arable lands. The river Brda runs from the north-west towards the south-east, in places almost in parallel to the field-forest borderline. In the past the river was a boundary river between the forest complex and farming areas. However after the Second World War the areas were afforested along the right riverside. This brought about a shift of the boundary several hundred metres westwards.

In the study area, as in the whole of Poland, westerly winds are predominant (Atlas of the Republic of Poland 1993-1997).

Damages in the forest stands of the Komorza Forest District caused by the wind activity in the year 2000, were much more severe in the volume of blown down woods as compared with other years, e.g. 1998-1999 and 2001-2002. Particularly considerable stem breakages occurred on 22nd June 2000. As a result of the windstorm moving from the west towards the east, damages were created near the road 237, which traverses the forest complex in subsections: 248a, 249g, 249h and 253c. Also further to the east, on the slope of the Brda river valley in the subsection 244c, on some small areas the forest was completely blown down. Also several hundred single windthrows were recorded.

Taking into account the distribution of surface damages in the vicinity of the field-forest borderline, and also a considerable share of secondary forests on formerly arable lands in this region, a hypothesis was expressed about the influence of those factors on the extent of damages in forest stands.

3 METHODS

The work was performed based on the geographic information system of the study area. In the first stage, the net of orthogonal coordinates was designed in the 1965 system. Subsequently, sheets of topographic maps in the scale of 1:25 000 were scanned and fitted in by means of the program MicroStation95 with the Descartes overlay. In the process of geometric rectification the maps were overlaid with the updated forest administration map in the scale of 1:20 000 and some historic topographic and forest economic maps from the 19th and beginning of the 20th century. Also satellite images Landsat 7ETM+ from the year 2000 were fitted as a raster information layer. In order to verify spatial distribution of secondary forests on formerly arable lands and places where forest was present continuously during last several centuries, a map of NDVI spatial variability was created, on the basis of the satellite image, as a separate information layer. By applying the GIS technology, spatial relations were defined between distribution of colours used on this map and polygons of secondary formerly arable forests on temporary and historic topographic and forest economic maps.

On the prepared raster layers, after x 1000 rescaling, current forest sections and subsections were digitized in the ESRI program ArcView 3.2. Distribution of wind-induced damages in the study area was charted by means of GPS receiver (Smart Antenna with the software Termap). Coordinates of tree throws and windthrows were imported into the project by means of the XYZ product in the program Microstation J/Polish. In case of surface damages, points along boundaries of deforestation areas were connected into polygons.

The prepared vector layer was connected with a database for the period 1998-2002 coming from the Information System of State Forests received from the Woziwoda Forest Inspectorate. The database comprised information about the forest address (district, section and subsection number), habitat type, stand quality classification, damage type, volume of timber in m^3 and date of logging, soil type (formerly arable, forest), forest canopy closure, name of a main tree species, its age and quantitative share.

With the help of a module for creating polygons from the program ArcView3.2, a buffer layer was created containing 86 zones in 10m interval. For a calculation reasons total amounts of damages in m^3/ha were presented in buffers every 100m. The zones were arranged from the field-forest boundary far into the forest complex determined on the base of previously digitized forest sections and sub-sections. After that, with the method ‘linking of topics’, a buffer layer was merged with a layer of digitized forest subsections using their gravity centres. For this operation the overlay Spatial Analyst – GeoProcessing Wizard was applied.

From the tables obtained after merging of both topics, data concerning timber volume were selected for a given forest sub-section, its area and location in a given buffer zone, i.e. a distance interval from the field-forest boundary. A range of wind-induced damages in m^3 was divided by an area of a given forest subsection. Calculated magnitudes of injuries were summed up separately for every buffer zone. From the created table, containing 2 vectors of figures: a volume of obtained timber in m^3 per ha and a distance of 86 buffer zones from the field-forest boundary in metres, a correlation coefficient was calculated and a function expressing relation between those parameters was defined. The calculations were repeated for data obtained for buffer zones in 100m intervals. Computer programs Statistica 5.0 and CExpert were applied for the calculation.

4 RESULTS

The total area of the forest subsections located within the study area amounted to 1682.62 ha. Analysis of the data coming from historic forest inventory books, old topographic maps, forest administration maps, and the satellite image dated 2000 year, it was ascertained that secondary forests on formerly arable lands covered ca. 8333.85ha, which made up 50.8% of the study area. Forests on the soils, which were not used for farming in the past, covered ca. 808.6 ha and thus 49.23 %**.**

Three surface damages of 0.23 ha, 0.44 ha and 0.53 ha area, and several hundreds of single windthrows and windfalls were recorded in the study area, as a result of the hurricane on 22nd June 2000. The total amount of the timber obtained from those damages amounted to 4,478.62 m^3, of which 3,831.73 m^3 in forests on formerly arable lands and 646.89 m^3 on forest soils. After converting those numbers to forest categories, they amounted to 4.6 m^3/ha and 0.8 m^3/ha respectively. Damages in the secondary forests on formerly arable soils constituted 84.37% of all losses and in the remaining forests only 15.63%. Pinewood dominated in the obtained timber. It comprised 92.64% of the total volume; beech wood made 4.48%, alder wood 1.35%, birch wood 1.35%, and oak wood only 0.17%. Most of the timber was obtained from forest stands 41-60 years old and 61-80 years old, i.e. 41.27% and 27.51% respectively. Most of the damages (32.76%) occurred on the most fertile forest habitats which bordered upon the field-forest boundary. High fertility of habitats indicates that those were formerly arable forests and pine monocultures replacing previous deciduous forests.

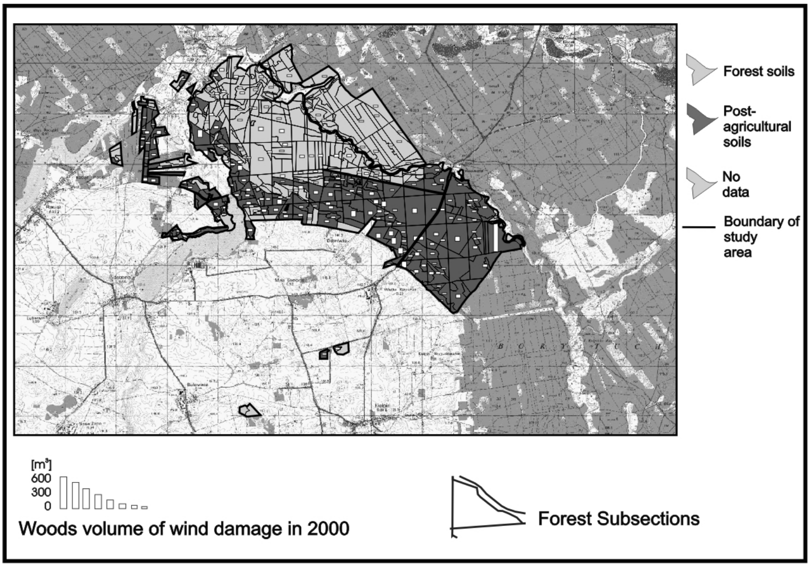

Figure 3. Spatial distribution of secondary forests on formerly arable lands and forests on forest soils; partition of the study area into forest subsections and volume of the logging timber from stem breakages in particular subsections

Most of the timber was obtained from stem breakages on habitats of mixed fresh pine forest, fresh pine forest, and fresh mixed forest, 46.73%, 26.60% and 24.58%, respectively.

From maps prepared in the GIS technology and from the drawn up histograms it stems that more severe injuries occurred along the field-forest boundary (Figs 3, 4). Along the distance of 860m far into the forest, 1004.92m^3/ha of the timber from stem breakages was obtained along the first 430m.

Within the next zone, i.e. 430-860m, the logging amounted to only 96.78m^3/ha. When analysing buffer zones in 10m interval it was ascertained that most of the damages, i.e. 103.09m^3/ha occurred within the 290-300m zone; within the zone of 140-150m - 65.18m^3/ha, 100-110m - 62.94m^3/ha, 0-10m - 57.74m^3/ha, 30-40m - 57.39m^3/ha, 160-170m - 52.27m^3/ha. In the remaining buffer zones logging was much lower (Fig. 5). Correlation coefficient expressing relationship between damages and a distance from the field-forest boundary (in 10m interval) reached value of 0.61.

When analysing 100m intervals it was ascertained that most of the damages occurred in the 0-100m zone, i.e. $373.5 m^3/ha$, then in the 200-300m zone, $264.06 m^3/ha$, and 100-200m, $212.7 m^3/ha$. It made 33.98%, 24.02% and 19.35% respectively. All together along the forest distance of 300m, 77.35% of damages were recorded. For the calculation carried out in 100m interval, the function expressing the relationship between a magnitude of damages and a distance from the field-forest boundary is presented in Fig. 6. The model equation for this relationship is

$$Y = 408.87607 - 1.0036329X + 0.0006126X^2,$$

whereas the correlation coefficient reached a value of 0.93.

5 DISCUSSION AND CONCLUSIONS

Much windthrow research has been conducted in Europe, Australia and America within the past three decades. These kinds of damages were considered to be a consequence of global change or the decreasing of forest areas enhancing those changes. In several studies of this kind, methods of remote sensing and GIS technology were applied, among them also computer programs employed in the present study (e.g. Foster & Goose 1992, Wright & Quine 1993, Lekes & Daudul 2000, Mitchell et al. 2001, Quine & Bell 1998).

With the help of these methods, the frequency of stem breakages and wind-induced damages was compared in forests of various history, both natural and forest plantations (Quine et al. 1999). Also several miscellaneous vegetation factors were investigated, among them those which influence spatial structure and range of damages, like species composition of forest stands, canopy architecture, height and breast height diameter (Peltola et al. 2000, Wilson & Oliver 2000) and site factors, like elevation and exposure (Peterson & Pickett 1990). Complex analysis of various factors influencing range and distribution of damages has been presented in numerous articles (Mayer 1989, Peterson 2000, Whigham et al. 1999, Ni Dhubhain et al. 2001) and special publications (e.g. Coutts & Grace, eds 1995). Whereas Kellomäki and Peltola (1999), among main factors affecting spatial distribution and range of damages, quoted proximity of forest edge. Also Hassinen et al. (1998), Campbell (1997), Ruel et al. (1998) and Gardiner et al. (2000) emphasized the importance of this factor. In our work it was proved that damages originate in close vicinity of a forest edge. A similar relationship was confirmed by Laurance et al. (1998) for forests from the tropical zone. Several researchers pointed out that besides a field-forest borderline, the edge effect could also occur on clearings located within forest complexes.

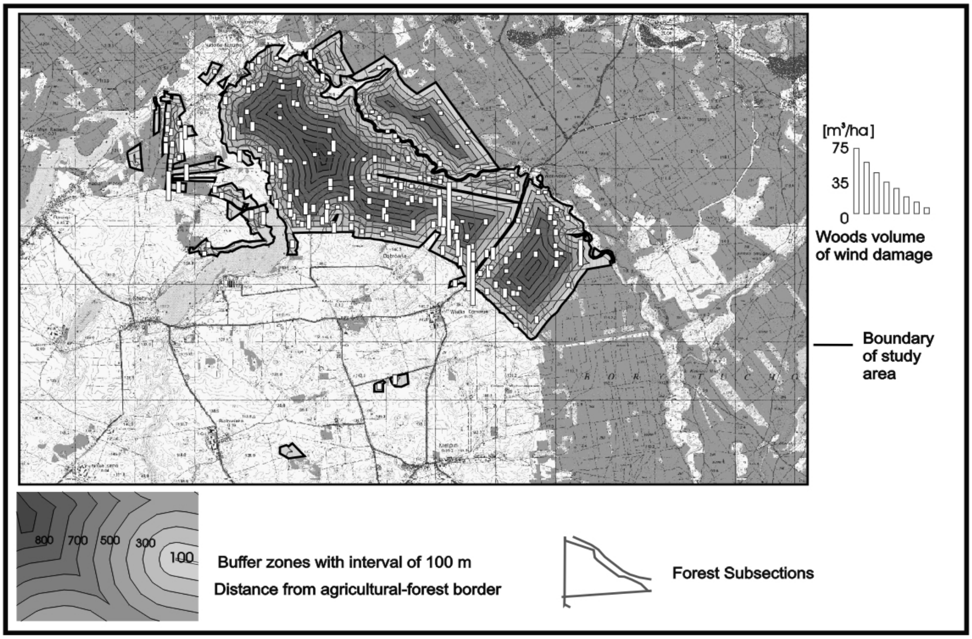

Figure 4. Volume of the logging timber in successive buffer zones arranged in 100m intervals from the field-forest borderline

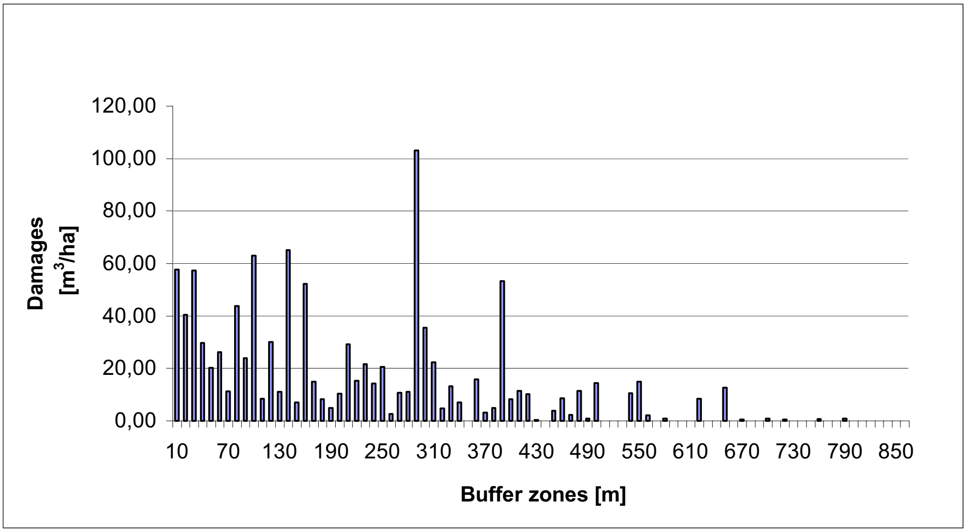

Figure 5. Volume of the logging timber in 86 buffer zones arranged in 10m intervals from the field-forest borderline

In the analysed Forest District of Komorza the range of damages was surely enhanced by the traffic route running across the forest complex. The importance of this landscape element was stressed by Ruel (2000).

The history of the landscape use has a considerable influence on the spatial pattern of windthrow damages in Bory Tucholskie Forest. Several secondary forests in this region occur on poor sandy soils. After their degradation and lying fallow, dry or ericaceous pine forests developed there. This kind of forest occupies small areas among large forest tracts, which have always grown on forest soils. The NDVI indicator of such secondary forests is usually lower, as their green biomass is smaller than the biomass of fresh pine forest developing on permanently forest soils. A different situation is observed in forests neighbouring large farming areas, which takes place in the studied fragment of the region near Tuchola and Wielka Komorza. Agricultural soils are fertile here. Formerly arable soils, where the forest was restored, are also characterized by high fertility. Their green biomass is higher than biomass of pine plantations on forest soils on the habitat of fresh pine forest. Their NDVI reaches a high value too. With large farming areas secondary forests usually border directly on fields or meadows. The high content of nutrients induces high above-ground biomass, and consequently the ratio of above-ground to underground parts is disturbed. A root system does not withstand overpressure and with strong gusts of wind windthrows take place because trees break**.** Low resistance against the wind is intensified by pathogens, fungi and insects, which reduce the hardness and elasticity of a trunk's tissues. Those factors caused that along the field-forest boundary in the Komorza Forest District wind-induced damages were excessive.

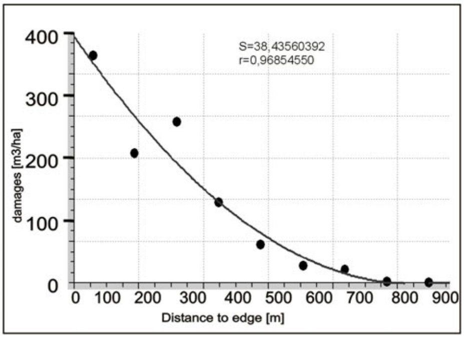

Figure 6. A function expressing relationship between volume of the logging timber and distance from the field-forest borderline in 100m intervals

For spatial analysis of windfalls, methods of satellite remote sensing were applied which today represent the basic tool for monitoring of forest conditions and landscape structure (Kennedy 1997, Lindemann & Baker 2001).

The Landsat 7ETM+ image, employed in the present study, proved to be useful for distinguishing forests growing on poorer or more fertile soils from soils in typically fresh pine forests, dominating on permanent forest soils. The spatial resolution of the satellite scanner allows also the identification of some larger forest gaps. To recognise smaller gaps, root breakages or stem breakages, a higher resolution is required. Changes in canopies resulting from dropping out of single trees, were studied by Smith (1999) applying images with a resolution of 4m. And thus this condition can be fulfilled by IKONOS images, which lately are more and more often used for analysing changes in vegetation structure (Franklin et al. 2001, Tanaka & Sugimura 2001, Asner et al. 2002, Oudemans et al. 2002).

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