

Application of Black-Bridge Satellite Imagery for the Spatial Distribution of Salvage Cutting in Stands Damaged by Wind

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Abstract

Salvage logging is performed to remove the fallen and damaged trees after a natural disturbance, e.g., fire or windstorm. From an economic point of view, it is desirable to remove the most valuable merchantable timber, but usually, the process depends mainly on topography and distance to forest roads. The objective of this study was to evaluate the suitability of the Black-Bridge satellite imagery for the spatial distribution of salvage cutting in southern Poland after the severe windstorm in July 2015. In particular, this study aimed to determine which factors influence the spatial distribution of salvage cutting. The area of windthrow and the distribution of salvage cutting (July–August 2015 and August 2015–May 2016) were delineated using Black-Bridge satellite imagery. The distribution of the polygons (representing windthrow and salvage cutting) was verified with maps of aspect, elevation and slope, derived from the Digital Terrain Model and the distance to forest roads, obtained from the Digital Forest Map. The analysis included statistical modelling of the relationships between the process of salvage cutting and selected geographical and spatial features. It was found that the higher the elevation and the steeper the slope, the lower the probability of salvage cutting. Exposure was also found to be a relevant factor (however, it was difficult to interpret) as opposed to the distance to forest roads.

Keywords: forest engineering, remote sensing, windthrow, sanitation harvest

1. Introduction

Strong winds can be a severe threat to forests. The windstorms called Lothar and Martin, reaching speeds of 198 km/h, caused the deaths of 140 people and damage estimated at 9.9 billion € (including over 150 million m³ of damaged trees) in December 1999 in France, Switzerland and Germany (Schwarz et al. 2003, Schindler et al. 2009). The windstorm called Guldrun, reaching speeds of 165 km/h, damaged more than 75 million m³ of forests in Denmark, Sweden and Estonia and killed 7 people in January 2005 (Valinger and Fridman 2011). In January 2007, windstorm Kyrill totally or partially damaged vast areas of forest in all zones of the Šumava and Bayerischer Wald national parks, which are situated on either side of the state border between the Czech Republic and Germany.

The volume of fallen timber approached 850 000 m³ (Klimanek et al. 2008). In December 2014, a warm mountain wind (Halny) caused damage to 50 000 m³ of forests in Tatra National Park in Poland (Bruchwald and Dmyterko 2010, 2011, 2012).

There are several types of datasets that can be used to delineate areas of windthrow. Some researchers performed their analyses based on optical datasets provided by sensors that receive a natural radiance signal reflected by the ground features: aerial (Honkavaara et al. 2013) and satellite imagery (Ciesielski et al. 2016). Others performed their analyses based on datasets provided by sensors that produce and receive an artificial radiance signal: radar (Fortuna et al. 2015) or LIDAR (Nystrom et al. 2014). Some of them performed their analyses using traditional approaches, such as a local survey supported by GPS (Koziański and

Table 1 Datasets used by various researchers to determine area of windthrow

Data sets	Literature
Aerial imagery	Wężyk et al. 2006, Honkavaara et al. 2013
Satellite imagery	Pleshikov et al. 1998, Maire and Yesou 2003, Schwarz et al. 2003, Yesou et al. 2003, Taguchi et al. 2005, Gancz et al. 2010, Rich et al. 2010, Valinger and Fridman 2011, Koziński and Nienartowicz 2013, Xiaoming and Benzhi 2013, Baumann et al. 2014, Fortuna et al. 2015, May et al. 2015, Fortuna et al. 2015, Ciesielski et al. 2016
Radar data	Fransson et al. 2002, Maire and Yesou 2003, Schwarz et al. 2003, Folkesson et al 2008, Fortuna et al. 2015
Lidar data	Yesou et al. 2003, Taguchi et al. 2005, Honkavaara et al. 2013, Nystrom et al 2014
GPS	Wężyk 2006, Koziński and Nienartowicz 2013
Local survey	Pleshikov et al. 1998, Scott et al. 2005, Rich et al. 2010, Ruel et al. 2013

Nienartowicz 2013) and a local survey alone (Rich et al. 2010, Table 1).

Researchers used several methods to delineate areas of windthrow. One group of methods requires the use of vegetation indices – mathematical combinations of spectral band values representing the vegetation health condition, e.g., Normalized Difference Vegetation Index (NDVI) or Disturbance Index (Ciesielski et al. 2016, Baumann et al. 2014). There is also a Principal Components Analysis approach, which produces a set of artificial bands sorted by their relative relevance and therefore their classification usefulness (Fortuna et al. 2015). A Tasseled Cap transformation is used to determine brightness, greenness and wetness, which are useful for further classification using supervised classification algorithms, such as Support Vector Machine (Baumann et al. 2014). An Artificial Neural Network is a machine learning method used for classification purposes and works similarly to human brain cells (Hanewinkel et al. 2004). When raster and vector lay-

ers are available, GIS analysis can be performed using standard computer software. Statistical modelling may also be helpful, starting from simple statistical analyses (Ruel et al. 2013) and ranging from regression models (Valinger and Fridman 2011) to more advanced statistical models (Byrne and Mitchell 2013, Table 2).

Among the factors that increase the susceptibility to windthrow in forest stands, the ones often brought up by researchers are those related to:

- ⇒ topography – including elevation, slope and aspect (Ciesielski 2016)
- ⇒ climate (Bruchwald and Dmyterko 2010, 2011, 2012) – especially wind characteristics (Schindler et al. 2009, Ruel et al. 2013)
- ⇒ ground characteristics – lithology and soils (Ionut and Bogdan 2012)
- ⇒ characteristics of trees and stands – age, height, breast-height diameter, crown cover, species composition (Bruchwald and Dmyterko 2010, 2011, 2012), crown parameters (Ionut and Bogdan

Table 2 Methods used by various researchers to determine area of windthrow

Methods	Literature
Vegetation indices (NDVI, NDVI_RE, gNDVI, ARVI, SAVI, EVI, Disturbance Index, etc.)	Gancz et al. 2010, Koziński and Nienartowicz 2013, Xiaoming and Benzhi 2013, Fortuna et al. 2015, Baumann et al. 2014, May et al. 2015, Ciesielski et al. 2016
Principal Component Analysis	Gancz et al. 2010, Fortuna et al. 2015
Tasseled Cap & Support Vector Machine	Baumann et al. 2014
Cluster analysis	Ruel et al. 2013
Artificial Neural Networks	Hanewinkel et al. 2004
GIS analysis	Pleshikov et al. 1998, Wężyk et al. 2006, Ionut and Bogdan 2012
Simple statistical analyses	Taguchi et al. 2005, Ionut and Bogdan 2012, Ruel et al. 2013
Regression models	Jalkanen et al. 2000, Mitchell et al. 2001, Hanewinkel et al. 2004, Scott et al. 2005, Kamimura et al. 2008, Rich et al. 2010, Valinger and Fridman 2011
Advanced models	Ancelin et al. 2004, Hanewinkel et al. 2004, Blennow and Salnass 2004, Achim et al. 2005, Gardiner et al. 2008, Bruchwald and Dmyterko 2010, 2011, 2012, Byrne and Mitchell 2013

2012), volume (Klimanek et al. 2008), health condition and root system (Koziański and Nienartowicz 2013)

⇒ spatial characteristics – forest area (Ionut and Bogdan 2012), distance to forest border or clear-cut areas (Koziański and Nienartowicz 2013)

⇒ anthropogenic factors – thinning (Ruel et al. 2013) and planting (Klimanek et al. 2008).

The risk of windthrow can be estimated using values and factors. The windthrow risk model constructed for Poland by Bruchwald and Dmyterko (2010, 2011, 2012) uses values that range between 0 and 3. The higher the value of the index, the greater the probability of windthrow that is estimated for each forest stand. The model also considers 10 factors: stand age, species composition, mean tree height, tree slenderness, density of trees, forest habitat type, geographical region, volume of trees salvaged within the previous 10 years, elevation, slope and aspect. The most important factors were species composition, mean height, stand volume and elevation.

Although methods of estimating post-windthrow damage and modelling the influence of particular variables were reviewed in several research articles, there is no work that has elaborated on the spatial distribution of post-windthrow salvage cutting with regard to elevation, slope, aspect and distance to roads or forest borders. It might be assumed that salvage cutting would be performed towards forest roads because it is easier to transport the cut trees where they can be loaded onto trucks, as well as downhill (excluding steeper slopes). The distribution of salvage cutting may also be dependent on sunlight aspect (due to the higher bark beetle outbreak risk) and elevation above sea level. A proper order of removing windthrow has fundamental meaning in order to collect the most valuable merchantable timber and thereby to minimize the financial loss. This raises the following question: is the removal of the windthrow provided only in order to minimize the financial loss, or is it influenced by other factors, such as topography or distance to forest roads?

The objective of the present research was to determine the most important factors influencing the spatial distribution of salvage cutting performed after the downburst in two periods – between 11 July 2015 and 31 August 2015 (salvage cutting I) and between 31 August 2015 and 22 May 2016 (salvage cutting II). The periods of cutting were determined by the Black-Bridge time-series satellite imagery acquisition dates, but they also represent two stages of salvage cutting performed by foresters – the initial stage performed intensively right after the windthrow, and the second

stage performed methodically over a longer period of time. The use of two separate satellite images enables the objective evaluation of the progress of windthrow removal performed by Forest Service workers. Aspect, altitude (height a.s.l.), slope, distance to forest roads and windthrow distribution were used as factors that could influence salvage cutting distribution and progress. Therefore, those factors were used as independent variables for statistical modelling (named as probability in modelling) in order to determine whether the distribution of salvage cutting depended on those variables.

2. Materials and Methods

2.1 Study area

The Międzyzylesie Forest District is situated in the southwestern part of Poland, in the area of the Kłodzka Basin. The total area of the forest district is approximately 10 230 hectares. The area of coniferous forest is approximately 7520 hectares, which is approximately 75% of the whole forest area. The remaining 10 and 15% are broadleaved and mixed forests, respectively. The Międzyzylesie Forest District is situated in a transitional climatic zone, with a slight influence of the continental climate (Woś 2012). The average temperature is approximately 7.4 °C, and the annual difference between the highest and lowest mean temperature reaches 19.3 °C. The annual precipitation is approximately 599 mm (IMGW 2017). In the area of the Międzyzylesie Forest District, there are local topographic dips (e.g., Kłodzka Basin) and hills (the Śnieżnik Massif and the Bystrzyckie Mountains), which surround the basin from the east and west. They are separated by the Międzyzyleska mountain pass and comprise a watershed between the Baltic Sea and Nordic Sea drainage basins (Fig. 1).

The location of the study area in the Kłodzka Basin and different topography (diversified elevation, slope and aspect according to windthrow distribution, subchapter 2.2) lead to division of the study area into two smaller study sites – the Śnieżnik Massif (the eastern part) and the Bystrzyckie Mountains Massif (the western part).

2.2 Windthrow in Międzyzylesie

On the night from 7 to 8 July 2015, between 3 and 4 am, a massive atmospheric phenomenon, a downburst, occurred in the Międzyzylesie Forest District of Poland. It is often confused with a tornado because of the amount of damage, but it manifests itself differently. According to Mason (2009), a downburst is a

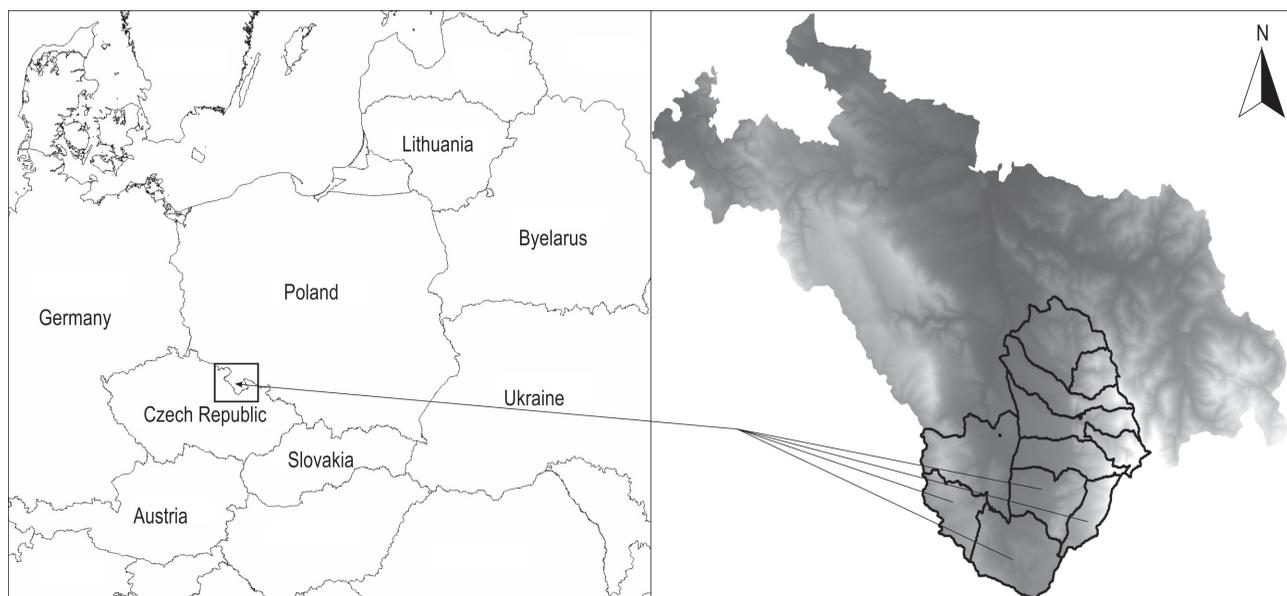


Fig. 1 Location of the study area within Europe (left picture) and within the Kłodzka Basin (right picture) (Międzyzylesie Forest District – black lines represent the border of forest sub-districts with marked areas of interest)

strong downdraft that induces an outburst of damaging winds on or near the ground. It could also be de-

finied as a damaging wind with a peak gust greater than 18 m s^{-1} , but this is not strictly applied throughout



Fig. 2 Damage caused by downburst in Międzyzylesie Forest District (source: www.miedzylesie.wroclaw.lasy.gov.pl/)

historical discussions of these events. The downburst is divided into two categories according to the spatial extent of the outflow: microbursts – events with a diverging wind extent less than 4 km – and macrobursts – events with an extent greater than 4 km. Microbursts could produce wind gusts as high as 75 m s^{-1} , while macrobursts, due to their larger scale, could produce wind speeds up to 60 m s^{-1} . Microbursts are generally found to occur for only 2 to 5 minutes, while macrobursts often last up to 30 minutes.

The total amount of windthrow was estimated at approximately $103\,000 \text{ m}^3$ by the local foresters and at approximately $160\,000 \text{ m}^3$ by using satellite imagery to estimate the area of windthrow and data concerning the mean volume of forest stands obtained from the State Forest Information System (SILP) database (Ciesielski 2016). However, according to the local windthrow risk model constructed by Bruchwald and Dmyterko (2010, 2011, 2012), there was an estimated $168\,000 \text{ m}^3$ of damaged timber.

2.3 Spatial data

The base material used for the analysis were Black-Bridge satellite images with a spatial resolution of 6.5 metres (5 metres after the resampling) and a radiometric resolution of 12 bits (16 after the atmospheric correction). The images consisted of 5 spectral bands: blue (440–510 nm), green (520–590 nm), red (630–685 nm), Red-Edge (690–730 nm) and near infrared (760–850 nm). The images were modified by atmospheric and radiometric corrections and were orthorectified using a Digital Elevation Model (DEM). The final product was a package of five satellite images taken in five spectral ranges. The Black-Bridge satellite images were taken for four forest districts on the area of the Kłodzka Basin (including Międzyzlesie Forest District) three times a year. The analysis was performed using the images taken four times: 6–12 June 2015, 11 July 2015, 31 August, 2015 and 22 May 2016.

The entire area was also scanned in 2012 using an Airborne Laser Scanning system, which produced a DEM (spatial resolution 0.5 m). The average density of the points was 6 per m^2 , and the accuracy equalled 0.15 m (Z plane) and 0.2 m (X, Y plane). The image was registered in the Polish National Geographic Coordinates System PUWG 1992 and 2000. Based on the DEM, the following rasters were generated in an ArcGIS 10.3 (ESRI, USA) environment: slope (spatial resolution 0.5 m) and mountain aspect (spatial resolution 100 m). Mountain aspect is understood as the compass direction that a slope faces. In the case of mountain aspect raster, it was necessary to resample it from 0.5 to 100 m resolution in order to acquire the information

about the whole slope. The analysis also used shape file vector data provided by the office of the Międzyzlesie Forest District (mainly public and forest roads).

2.4 Data processing

The first step of the analysis was to calculate the Normalized Difference Vegetation Index (NDVI) of the three Black-Bridge images from 11 July 2015, 31 August 2015 and 22 May 2016. The calculation was performed using the Raster Calculator tool from ArcGIS 10.3 (ESRI, USA). The raster images, representing values of the NDVI, were then classified into forest ($\text{NDVI} > 0.3$) and non-forest ($\text{NDVI} < 0.3$) areas (meadows, agricultural lands, urban lands). The NDVI-based classification of the three Black-Bridge satellite images of two classes (forest and non-forest) was evaluated using a set of control points. The overall classification accuracy was 91% (for the image taken on 11 July 2015), 92% (for the image taken on 31 August 2015) and 94% (for the image taken on 22 May 2016).

The clouds, shades, fogs, roads (with a road-width buffer zone), non-forest areas and areas where vegetation cover was lower than 1.0 m were clipped out from the images. The final image was filtered using a Majority Filter tool in ArcGIS 10.3 (ESRI, USA) with a 3×3 pixel moving window parameter. The use of Majority Filter made it possible to remove noise resulting from image classification. The polygons representing non-forest areas on the images taken in July 2015, which were absent until the end of August 2015, were deleted. The polygons representing non-forest areas on the image taken on 31 August 2015, which were absent until 22 May 2016, were also deleted. It is possible that these polygons represented areas of natural succession.

The buffer zones around forest roads were generated using the Multiple Buffer tool in ArcGIS 10.3 (ESRI, USA). The DEM was used to produce maps of slope, aspect and elevation, divided into classes (Table 3). To perform statistical analysis, a set of points was generated and randomly put on the areas of:

- ⇒ windthrow (based on the satellite image taken on 11 July 2015)
- ⇒ salvage cutting I – the area of initial salvage cutting performed between 11 July and 31 August 2015
- ⇒ salvage cutting II – the area of further salvage cutting performed between 31 August 2015 and 22 May 2016
- ⇒ other areas.

Random points were generated separately for the Bystrzyckie Massif (the western part) and the Śnieżnik Massif (the eastern part) – approximately 1000 points each (approximately 250 points for each class).

Table 3 Division of aspects, slopes and elevations

Aspect	Slope, degrees	Elevation, m a.s.l.
N, north	<5 degrees	400–500
NE, north-east	5–10	500–600
E, east	10–15	600–700
SE, south-east	15–20	700–800
S, south	20–25	800–900
SW, south-west	>25	900–1000
W, west		1000–1100
NW, north-west		1100–1200
		1200–1300
		1300–1400

2.5 Statistical analysis

There is a wide range of methods that enable comparisons among the influence of various factors on the dependent variable of interest, including regression analysis, analysis of variance, various types of linear and non-linear models and principal components analysis. However, in this analysis, the response variable is nominal with a few levels, and particular areas are defined using quantitative predictors. In this case (qualitative response variable and both qualitative and quantitative predictors), a Multinomial Logistic Regression (MLOGIT) approach was used (Hosmer et al. 2013) in order to assess which factors had the greatest influence on the windthrow removal process performed by Forest Service workers.

The MLOGIT method models nominal outcome (response) variables, and the log odds of the outcomes were modelled as a linear combination of predictors. In this work, the dependent variable was the type of area (forest stands, windthrow, salvage cutting I, salvage cutting II), and the explanatory variables (predictors) were the elevation, steepness of slope and aspect (with north (N) as the reference direction).

The analysis was performed separately for the eastern and western regions to exclude possible mutual reduction of the variables on the opposite mountain ranges. The MLOGIT analysis is always held in accordance with the selected reference level (baseline). If the forest stands were the reference level (baseline), the model of the log odds of being in one area category vs. another (reference/baseline) would have the following form:

$$\ln \left(\frac{P(\text{area} = \text{windthrow})}{P(\text{area} = \text{forest_stand})} \right) = b_{1,0} + b_{1,1} \times \text{Altitude} + b_{1,2} \times \text{Slope} + b_{1,3}(\text{Aspect} = \text{NE}) + b_{1,4}(\text{Aspect} = \text{E}) + \dots b_{1,9}(\text{Aspect} = \text{NW})$$

$$\ln \left(\frac{P(\text{area} = \text{salvage_I})}{P(\text{area} = \text{forest_stand})} \right) = b_{2,0} + b_{2,1} \times \text{Altitude} + b_{2,2} \times \text{Slope} + b_{2,3}(\text{Aspect} = \text{NE}) + b_{2,4}(\text{Aspect} = \text{E}) + \dots b_{2,9}(\text{Aspect} = \text{NW})$$

$$\ln \left(\frac{P(\text{area} = \text{salvage_II})}{P(\text{area} = \text{forest_stand})} \right) = b_{3,0} + b_{3,1} \times \text{Altitude} + b_{3,2} \times \text{Slope} + b_{3,3}(\text{Aspect} = \text{NE}) + b_{3,4}(\text{Aspect} = \text{E}) + \dots b_{3,9}(\text{Aspect} = \text{NW})$$

Where:

- $P(\text{area} = \text{windthrow})$ probability that the analysed area falls into the »windthrow« category
- $P(\text{area} = \text{forest_stand})$ probability that the analysed area falls into the »forest stand« category (reference/baseline category)
- $P(\text{area} = \text{salvage_I})$ probability that the analysed area falls into the »salvage cutting I« category
- $P(\text{area} = \text{salvage_II})$ probability that the analysed area falls into the »salvage cutting II« category
- Altitude altitude in metres above sea level calculated from DEM
- Slope terrain slope calculated from DEM
- $\text{Aspect} = \text{direction}$ aspect (NE, E, SE, S, SW, W, NW), understood as the compass direction that a slope faces, considered as a change with respect to the reference N aspect

In this model, the dependent variable was the ratio of the probability of choosing one outcome category over the baseline category, i.e., odds, and the parameter next to the particular independent variable was interpreted as a slope in the linear regression model. The slope shows how the log odds change with an increase in this particular predictor by one unit (e.g., elevation by 1 m or slope by 1 degree) or changing its category from the baseline to

Table 4 Logit model’s parameters with »forest stands« as baseline

Logit model’s parameters with »forest stands« as baseline (A)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Windthrow (eastern part)	-0.1178	-0.0013*	0.0110*	0.0314	0.7454*	0.8658*	0.8577*	0.9741*	1.1822*	1.0647*
Windthrow (western part)	1.3154*	-0.0023*	-0.0220	-0.0534	-0.0528	0.3671	0.1861	0.5546*	1.8161*	0.6564*
Relative risk – transformed Logit model’s parameters (eparameter) with »forest stands« as baseline (B)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Windthrow (eastern part)	0.8889	0.9987*	1.0110*	1.032	2.1073*	2.3770*	2.3577*	2.6487*	3.2617*	2.9000*
Windthrow (western part)	3.7261*	0.9977*	0.9782	0.9480	0.9485	1.4436	1.2046	1.7412*	6.1480*	1.9278*
Logit model’s p-values with »forest stands« as baseline (C)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Windthrow (eastern part)	0.6838	0.0025*	0.0308*	0.9347	0.0268*	0.0216*	0.0072*	0.0000*	0.0000*	0.0000*
Windthrow (western part)	0.0002*	0.0020*	0.1870	0.8722	0.8388	0.2030	0.6052	0.0338*	0.0000*	0.0313*
Logit model’s parameters with »windthrow« as baseline (D)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Salvage cutting I (eastern part)	2.7924*	-0.0032*	-0.0091*	0.0517	-0.7055*	-1.0650*	-1.6820*	-0.7231*	0.1528	0.1253
Salvage cutting II (eastern part)	-0.0243	0.0003	-0.0144*	0.2070	-1.6752*	-0.2128	-0.0051	0.0022	0.0000	0.3143
Salvage cutting I (western part)	5.9989*	-0.0085*	-0.0455*	0.5894	-0.4211	0.8142*	-0.8411	0.2792	0.2640	0.4549
Salvage cutting II (western part)	1.7527*	-0.0011	-0.0473*	0.1828	-0.4626	-1.0929*	-0.2811	0.7990*	-0.7486*	-0.6989*
Relative risk – transformed Logit model’s parameters (eparameter) with »windthrow« as baseline (E)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Salvage cutting I (eastern part)	16.3201*	0.9968*	0.9909*	1.0530	0.4939*	0.3447*	0.1860*	0.4853*	1.1651	1.1350
Salvage cutting II (eastern part)	0.9760	1.0003	0.9857*	1.2299	0.1873*	0.8083	0.9949	1.0022	1.0001	1.3693
Salvage cutting I (western part)	402.9791*	0.9915*	0.9554*	1.8029	0.6563	0.4430*	0.4312	1.3221	1.3022	1.5761
Salvage cutting II (western part)	5.7701*	0.9989	0.9538*	1.2006	0.6296	0.3352*	0.7549	0.4498*	0.4730*	0.4970*
Logit model’s p-values with »windthrow« as baseline (F)										
Dependent variable	Intercept	b_altitude	b_slope	b_NE	b_E	b_SE	b_S	b_SW	b_W	b_NW
Salvage cutting I (eastern part)	0.0000*	0.0000*	0.0371*	0.8455	0.0381*	0.0065*	0.0001*	0.0072*	0.4771	0.5814
Salvage cutting II (eastern part)	0.9327	0.4234	0.0051*	0.4109	0.0000*	0.4904	0.9875	0.9926	0.9997	0.1484
Salvage cutting I (western part)	0.0000*	0.0000*	0.0261*	0.0794	0.1551	0.0156*	0.0891	0.2728	0.3357	0.1281
Salvage cutting II (western part)	0.0000*	0.0572	0.0176*	0.5781	0.1032	0.0011*	0.4397	0.0033*	0.0058*	0.0219*

* Statistically significant parameters ($\alpha=0.05$)

a given category (e.g., b1_3 (*aspect* = NE) means a change from the baseline northern to a given north-eastern aspect).

The parameter was transformed to the »relative risk« form – the ratio of the probability of selecting one outcome category over the probability of choosing the

baseline category – by its exponentiation: $relative_risk = e^{parameter}$

The MLOGIT model’s parameters were estimated using the »multinom« function from the »nnet« package (Venables and Ripley 2002) of »R« software (R Core Team 2016). The significance of the parameters was

analysed using Wald's z-test. To analyse the influence of the distance to forest roads on the spatial distribution of salvage cutting, simple chi-squared tests were performed separately for the eastern and western parts of the study site.

A cross-table analysis was also performed to analyse the process of merging smaller polygons into bigger ones.

3. Results

In both the eastern and western mountain ranges, the higher the elevation, the lower the chance for windthrow to occur (negative slope value with the Altitude predictor in Table 4A, $p=0.0025$ and 0.0020 , respectively, in Table 4C). In the eastern mountain range, the influence of slope was positive ($b_{\text{slope}}=0.0110$, Table 4A) and significant ($p=0.0308$, Table 4C), while in the western mountain range, the slope parameter was not significantly different from zero ($p=0.1870$, Table 4C). In the eastern mountain range, the probability of windthrow occurrence on the northern (N) aspect was lower than on any other aspect, or the probability of windthrow occurrence on any aspect was higher than on the northern (N) aspect, except the north-eastern (NE) one ($p=0.9347$, Table 4C). At the same time, in the western mountain range, the probability of windthrow occurrence on the northern (N) aspect was lower than on the western (W), south-western (SW) and north-western (NW) aspect ($p=0.0338$, <0.0001 , 0.0313 , respectively, Table 4C).

To analyse the areas of salvage cutting I and II, it was more convenient to reorganize the database and make the windthrow areas the baseline for the MLOGIT model instead of forest stands. Based on such a reformulation of the approach, it was possible to conclude that in both the eastern and western mountain ranges, the higher the elevation and the steeper the slope, the lower the probability was for »salvage cutting I« class to occur ($p<0.0001$, Table 4F). At the same time, in the eastern mountain range, the probability of »salvage cutting I« on the northern (N) aspect was higher than on the other four aspects: E, S, SE or SW ($p=0.0381$, 0.0065 , 0.0001 and 0.0072 , respectively, Table 4F). In the western mountain range, the probability of »salvage cutting I« on the northern (N) aspect was only higher than on the south-eastern (SE) aspect ($p=0.0156$, Table 4F). The steeper the slope, the lower the probability was for »salvage cutting II« to occur in both ranges ($p=0.0051$ and 0.0176 , respectively, Table 4F). In the eastern (E) mountain range, the probability of »salvage cutting II« on the northern (N) aspect is lower than on the eastern (E) aspect ($p<0.0001$). In the western

mountain range, the respective probability was higher on the four aspects (SE, SW, W, NW) than on the northern (N) reference one ($p=0.0011$, 0.0033 , 0.0058 and 0.0219 , respectively, Table 4F).

A separate analysis was performed to determine whether the distance from roads had an influence on windthrow and salvage cutting occurrence. In both cases, the distribution was similar (p -values= 0.1991 and 0.2133 for the eastern and western mountain ranges, respectively), which denotes no impact of the distance from roads on windthrow and salvage cutting occurrence.

The majority of polygons smaller than 0.1 ha were merged with the nearest polygons larger than 1 ha during the salvage cutting process. The migration from the lowest classes (<0.5 ha) to the classes above 1 ha accounts for 25% of all polygons. The area of windthrow polygons larger than 1 ha (after salvage cutting) became greater by 176%.

4. Discussion

This study confirms the usefulness of remote sensing data in forest management at the local scale. According to Grigilato et al. (2017), GIS has been applied successfully to harvesting, transportation engineering and tactical planning in forest operations management at the operational level (in terms of optimization, productivity and safety analysis) and will expand in the near future. On the other hand, Talbot et al. (2017) concluded that almost all applications of remotely sensed data in forest operations are still experimental and have a range of issues that need to be improved before widespread operationalization can occur.

An accurate delineation of areas of windthrow and salvage cutting proves that satellite imagery is a valuable and sufficient data source to update forest digital maps, especially in change detection, both natural and anthropogenic. The update of the Forest Digital Map in Poland is usually performed using GPS, and it is far from being cost- and time-efficient, while the accuracy is only up to 2 m. Remote sensing data should thus be considered as an alternative, time-efficient and relatively accurate data source (Weżyk 2010, Okła 2010).

Black-Bridge satellite imagery was used in the analysis. Its spatial resolution is 5 m, although it is not available for free. However, there is free satellite imagery available on the Internet, e.g., Sentinel-2, provided by the European Space Agency (ESA). Its spatial resolution is 10 m – worse than Black-Bridge, but good enough to perform change detection analysis after a severe windstorm (Einzmann et al. 2017). In

forestry, it is becoming more and more popular to use Unmanned Aerial Vehicles (UAVs). The disadvantage of a UAV is that it is not able to perform for very long and often needs a large space to start and land safely.

The information about the spatial distribution of windthrow and salvage cutting performed afterwards could become a basis to introduce a forest entrance ban, which is usually introduced after a site inspection, which does not include areas that are difficult to reach by Forest Service workers. Additionally, it provides an objective argument to convince the local society to remove fallen and damaged trees not only for safety reasons but also to prove that salvage cutting (often opposed by the ecologists) greatly reduces the risk of pest outbreak.

Due to climate change, the risk of severe windstorms and other extreme weather phenomena, the need to improve the decision-making process and quick access to spatial data are becoming more and more important.

There are many papers elaborating on the detection of windthrow and fires (Huang et al. 2010, Kennedy et al. 2010); however, there is still little known about the factors that influence the salvage logging distribution and order (when and where salvage cutting is performed). The decision regarding where to start salvage logging is far more important when the fragments of forest with damage are dispersed and occur in various topological and ecological conditions. A better understanding of the foresters' decision is needed to minimize the economic losses, even though removing damaged trees is controversial (Lang et al. 2009).

It was important to quickly perform the process of salvage cutting on a large scale because most of the forest stands in the Międzyzylesie Forest District are dominated by Norway spruce (*Picea abies* L.). If the damaged wood had been left until the next year, the probability of instant bark beetle (*Ips typographus* L.) outbreak and severe fires would have been increased. The appropriateness of salvage cutting was proven to be beneficial and was presented in many studies (Grodzki and Guzik 2009, Grodzki et al. 2010).

It should also be noted that damaged trees are not the only problem; by changing the spatial pattern of these resources, severe wind disturbances are known to significantly alter the successional dynamics of forests over the long-term, but outcomes are inconsistent and difficult to predict given the milieu of contributing factors (Everham and Brokaw 1996, Peterson 2000). Foster and Orwig (2006) suggest that wind-salvaged areas may experience more dramatic alteration of forest structure, soil resources, and

biogeochemical processes than windthrown areas alone.

According to Peterson et al. (2008), sapling density and species richness were not influenced by cumulative (windthrow, salvage cutting) disturbance severity in Tennessee (USA). Species diversity and the amount of compositional change showed an increase with increasing cumulative severity. Moderate-severity natural disturbances followed by moderate-intensity salvaging may have little detrimental effect on forest regeneration and diversity.

The occurrence of windthrow and the spatial distribution of salvage cutting may affect the carbon balance in a forest stand. Therefore, information about the current state of salvage cutting can be used in the modelling of the carbon balance.

Two management scenarios analysed by Schlesinger et al. (1990) had a strong influence on the carbon budget. All BAU (Business as usual) scenarios result in an above-ground as well as a below-ground carbon sink. The RLL scenario aims to reduce the number of large trees and, therefore, leads to a marked biomass decrease. Although soil carbon increases, the total carbon budget of the RLL (Reducing the number of large logs) scenarios becomes negative after 30 years. His results indicate that forest soils can profit only in a limited way from the increase in litter input. One reason could be that much of the litter consists of short-lived tissues, such as foliage and fine roots. They decompose quickly, and normally, only a small portion of their carbon contributes to persistent organic materials such as humus. Schlesinger and Lichter (2001) suggest that significant long-term net carbon sequestration in forest soils is unlikely.

The results achieved by Lüscher et al. (2002) further indicate that at the level of the national carbon budget, the scenario without clearing after storms shows only a slightly more positive carbon budget than the cleared scenario. The reason is that the amount of windthrown timber is large only on the local scale. On a national scale, windthrown timber from the past three storms made up only a small amount of the average annual timber harvest. The sensitivity of the decay rate of windthrown timber implies that the uncertainty of the decay rate has no significant impact on the national soil carbon budget. However, the decomposition of timber on storm areas could be even higher. With the absence of the tree layer, soil temperatures rise, which, provided there is enough moisture, causes more rapid mineralization of the accumulated organic debris and thus faster decomposition.

The results of this study may be used to calculate carbon budgets at local scales with the use of specialized

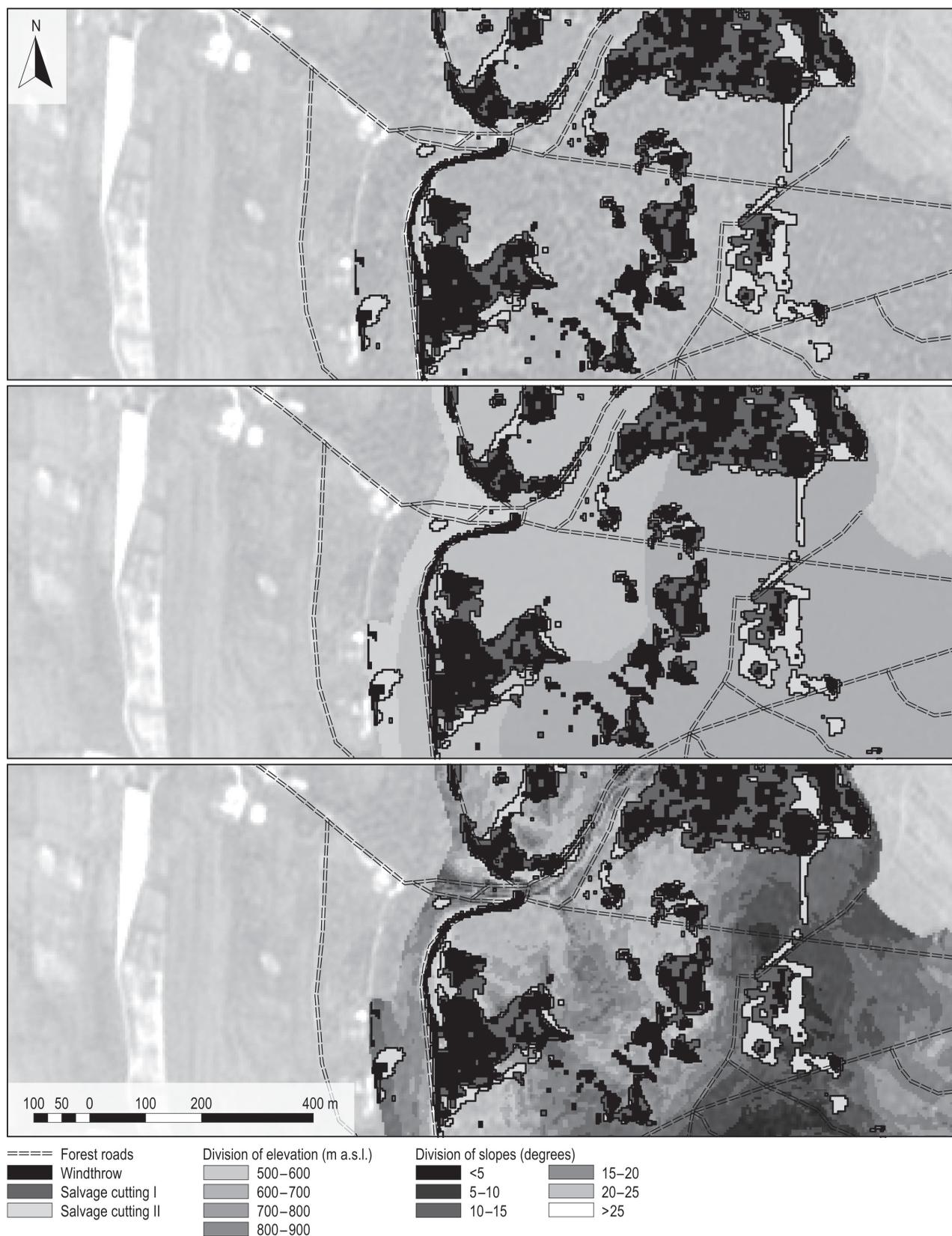


Fig. 3 Examples of salvage cutting spatial distribution – towards forest roads or in the opposite direction (first picture), on different elevation (second picture) and slope (third picture) classes

software, such as Carbon Budget Model Canadian Forest Sector-3.

It was assumed that salvage cutting would be performed towards forest roads and downhill, because it is easier to transport harvested trees where they can be loaded onto trucks. The distribution of salvage cutting may also be dependent on sunlight aspect due to higher bark beetle outbreak risk on trees exposed to sunlight after the windstorm. Additionally, slope and elevation a.s.l. can be influential, as it is more difficult for both men and machines to perform salvage cutting on these sites. Although the general rules are widely known, the actual process of removing windthrow is influenced by non-substantive factors, which do not come from the economic guidelines but rely on personal preferences and decisions of particular foresters.

It was concluded that, with a steeper slope and higher elevation, there is a lower probability of salvage cutting, which confirms the initial assumptions. Steep slopes and high elevation make salvage cutting too difficult both for men and equipment. The influence of aspect was found to be relevant but difficult to interpret. There is no evidence that salvage cutting is more probable among trees exposed to sunlight after the windstorm, nor downhill, as previously assumed. The distance to forest roads was found to be statistically irrelevant. The distribution of salvage cutting was partly influenced by smoothing the border of windthrow areas, cutting single trees left on the area of windthrow and the proximity to forest stand borders. This dependence was proven with the cross-table analysis and the visual interpretations of the most interesting examples (Fig. 3).

Further analysis is needed not only on other sites but also across Europe, because cultural, economic and anthropological aspects may also influence the distribution of salvage cutting.

5. Conclusions

In this paper, remote sensing data imagery was used to estimate the probability of salvage cutting after the windstorm in 2015 in southwestern Poland.

It was proven that delineation of areas of windthrow and salvage cutting using satellite imagery is accurate enough to update digital forest maps, especially regarding change detection, and should be considered as an alternative to traditional forest management.

According to the results of the performed analysis, it might be concluded that, with steeper slopes and higher elevations, the probability of salvage cutting

will be lower. The distance to forest roads does not influence the spatial distribution of salvage cutting. The influence of aspect on the spatial distribution of salvage cutting was found to be relevant but difficult to interpret.

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