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Influence of site conditions on the windstorm impact: A case study of the High Tatras foothills in 2004

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Abstract: The calamity situation in the forests of the Tatra National Park, caused by a windstorm on the 19th of November 2004, had widespread damaging effects. The wind calamity caused slashes and wind throws as well. The aim of our paper is to describe influence of the site conditions (parameters of vegetation, soil and georelief) on the windstorm impact at chosen representative localities in the High Tatras foothills. The results obtained by methods of large-scaled geo-ecological field research, remote sensing, geographical information system environment and statistical analyses are presented in this paper. Geotops of saddles, elevations of moraine and colluvial slopes with planted spruce growths and spruce-bilberry forests have been damaged most. Small damage was recorded on geotops of erosion slopes with spruce-bilberry and fir forests, depressions and slopes of moraines covered with mixed pioneer forests. The most important were herein the characteristics of the rock skeleton (mainly size and weathering), soil texture, georelief orientation or wind exposition. The important role of the altitude probably expresses a regional positional factor (distance from the uphill line).

Key words: windstorm, sites, geoecological research, statistical methods, the Tatra National Park

Introduction

Strong wind events impact forests all over the globe in both temperate and tropical regions. Understanding of the wind forces impact on trees (Wood, 1995) and the use of a geographical information system to investigate storm damage to trees (Wright & Quine, 1993) are actual problems of current landscape-ecological and forestry research. The morphological effect of these events (wind throws and its other consequences; e.g. Martin & Timmer, 2006; Philips & Park, 2009) is also very important implication.

The calamity situation in the forests of the Tatra National Park (TANAP), caused by the windstorm on the 19th of November 2004 is distinctive due to its damaging dimension. The area of TANAP was affected by wind with a speed up to 200 km per hour. More than 120 square kilometres of foothill forest were damaged. The wind calamity caused slashes and wind throws as well (Fig. 1).

The catastrophic windstorm is a repetitive phenomenon in the region. Similar (but less catastrophic) events occurred in 1898, 1915, 1919, 1968, 1980 and 2002 (Koreò, 2005). The Tatras with very rugged topography form various conditions for air flows and local winds. Jeník (2000) terms this complex of natural phenomenon in mountain areas with local winds the anemo-orographic system. The windstorm had the character of a bora that thumbled over the Tatra ridges from the north and north-west and stuck the foothills, where maximum damage was recorded (Balon & Maciejowski, 2005). The current results of research from areas damaged by wind were already published (e.g. Fleischer & Matejka, 2007; Majlingová & Ponce (Eds.), 2007), but authors are mainly concerned with analytical investigation. Following examples from other regions (e.g. Kramer *et*

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Fig. 1. Slashes and wind throws in the affected area

al., 2001; Mikita *et al.*, 2009), we attempted at a wider, comprehensive geo-ecological approach.

The aim of our paper is to describe influence of the site conditions on the windstorm impact at chosen representative localities in the High Tatras foothills (Fig. 2). The results based on the large-scaled geo-ecological field research, remote sensing, geographical information system and statistical methods are presented in this paper. The preliminary published results (Minár *et al.*, 2008) were complemented by dataset spreading and use of new methods.

Material and methods

We can perceive the calamity situation after the Tatra windstorm as a reaction of local (topical) geosystems (geotops) to a disturbing input (Fig. 3). Every input disturbance affects mainly a part of elements and a part of the system interactions, which determines the local effect of the disturbance. Disturbance is manifested like wind throws and slashes that reduce abundance of tree layer. Properties of the geosystem elements (mainly vegetation, georelief, soils and substratum – see Fig. 3) were trailed for explanation of territorial differentiation of the disturbance.

The relationship between site conditions and the level of the vegetation cover damage (see Fig. 3) was investigated during a cameral stage of the research. The approach following methods of detailed field geo-ecological research and mapping (Minár *et al.*, 2001) was used for the collection of data in the field at several chosen parts of the High Tatras foothills, in the surroundings of permanent research fields assigned by the management of the Tatra National Park: Vyšné Hágy (reference, untouched forest), Tatranská Lomnica – Jamy (non-extracted forest), Danielov dom (extracted forest), Tatranské Zruby (extracted, burnt forest). We established out 260 research points (tesserae) in two research stages. The tesserae were localised in such a way, so that they record local differences between more and less damaged topical geosystems.

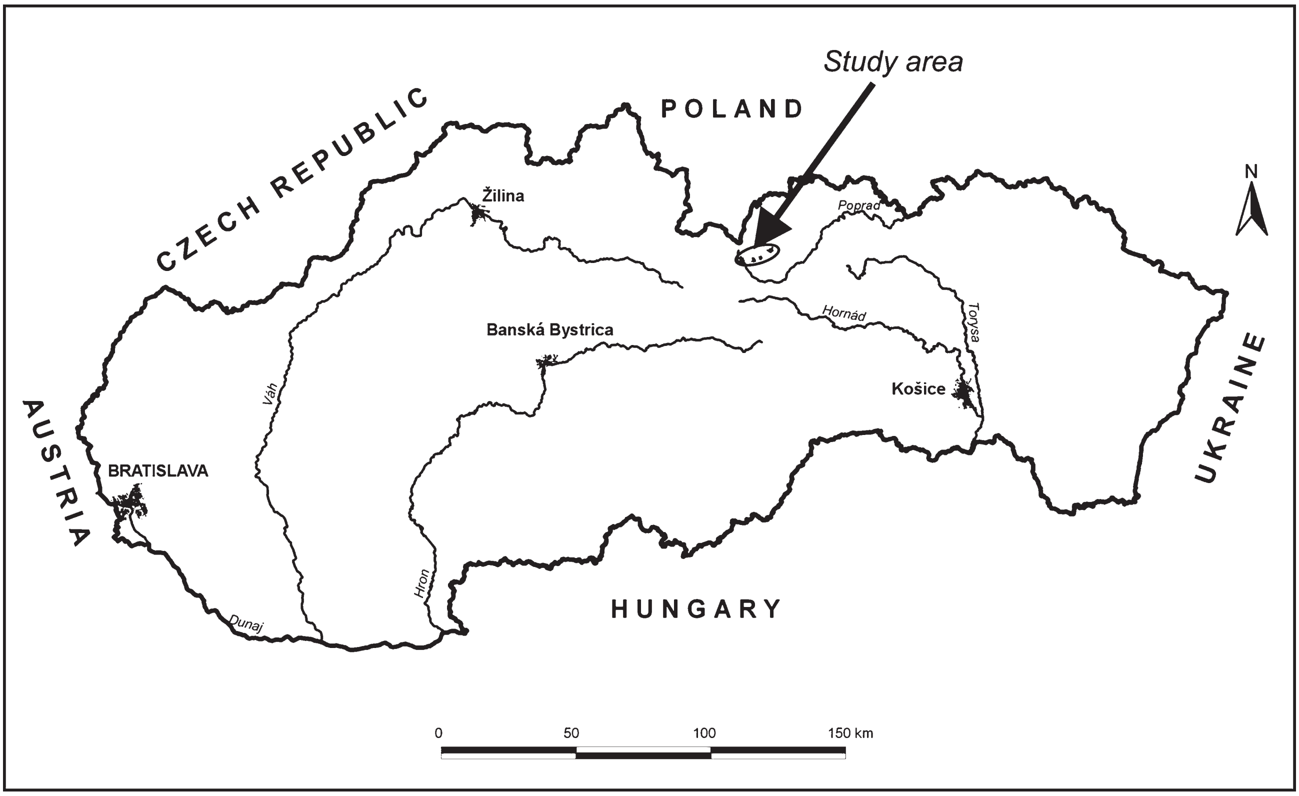

Fig. 2. Location of the study area

Classification of the tesserae into types of the geotops (topical physio-geographical units) and evaluation of their disturbance was the first used approach. We used georelief (landforms) as a leading factor of the classification.

Multiple regressions between indicators of the forest damage and geosystem characteristics (see Fig. 3) and an evaluation of types of geotops (which represent various sites) damage were the second crucial procedure of the analysis.

The first stage of the research (based on the information obtained from 110 research points) leads to ambiguous results. It only partially confirms a tendency of specific reactions of various sites (represented by tesserae) to windstorm disturbance. Statistical tests did not show the influence of abiotic characteristics on the disturbance intensity convincingly. Therefore, we focused on the solution of the following problems (Minár *et al*., 2008):

- the dataset should be completed to be more representative for particular types of sites;
- the location of new tesserae should result in the approach of the collected data to a normal distribution,;
- the definition of some used characters should be reassessed. Replacements of distance from uphill line by axis of maximally disturbed area or definition of 'damage contrast index' (expressing degree of damage of a tessera in comparison with the surrounding one) are examples.

The dataset was extended more than doubly (quite 260 research points compared to 110 from the first stage) creating the "*Basic dataset*". The dataset more closer to normal distribution of disturbance characteristics was then achieved by a random selection of data. The resulting dataset of 120 points is termed "*Normalized dataset*".

To bypass the influence of regional positional factors, the *Relative forest damage index* D_R was defined as a ratio of *Absolute forest damage* of a given site and its surroundings (see Fig. 3). Absolute forest damage of the surroundings was computed as a weighted mean of neighbouring geotops, where the length of the boundary was the weight. The non-point degree of the forest damage we define by using orthophotomaps of the area after calamity.

The damaged area is recorded in the remote sensing image by a change in the value of reflection surface. On the orthophotomap registered in the visible spectrum, the damage reflects shifts in brightness of the digital image from the dark (undamaged) to light values. To determine the degree of damage, a visual interpretation (Žihlavník & Scheer, 2001) was initially used, identifying various homogeneous areas examined in the field. Homogeneity was assessed using the area of interpretative signs. Comparison sites are made on the basis of observed values of reflection observation area. In each areas, the minimum, maximum and average value of brightness were determined. The values allow each other to compare the damaged areas. The maximum damaged area is the area with the highest average brightness. The least damaged area was a locality with the lowest average value of brightness. For the remaining areas, the degree of damage was determined in proportion to the two extreme values.

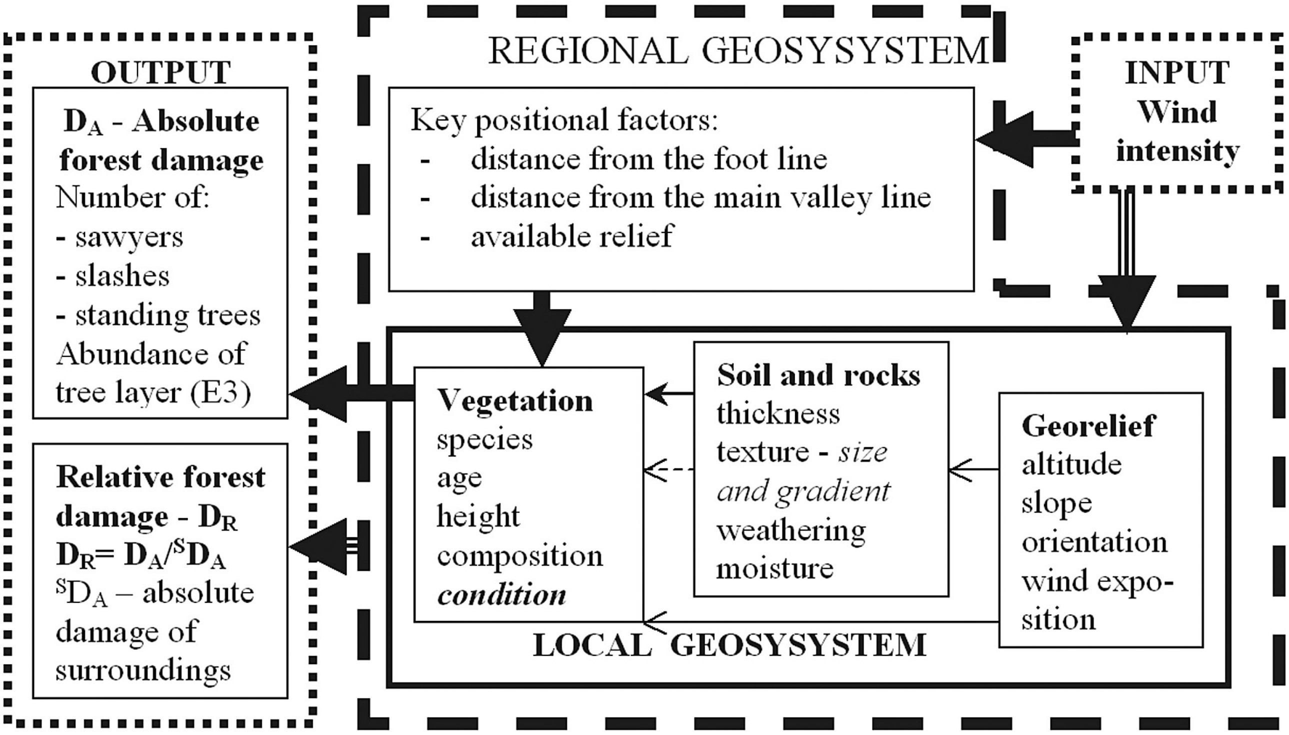

Fig. 3. System scheme of disaster and relevant properties of its elements (Minár *et al*. 2008, adapted)

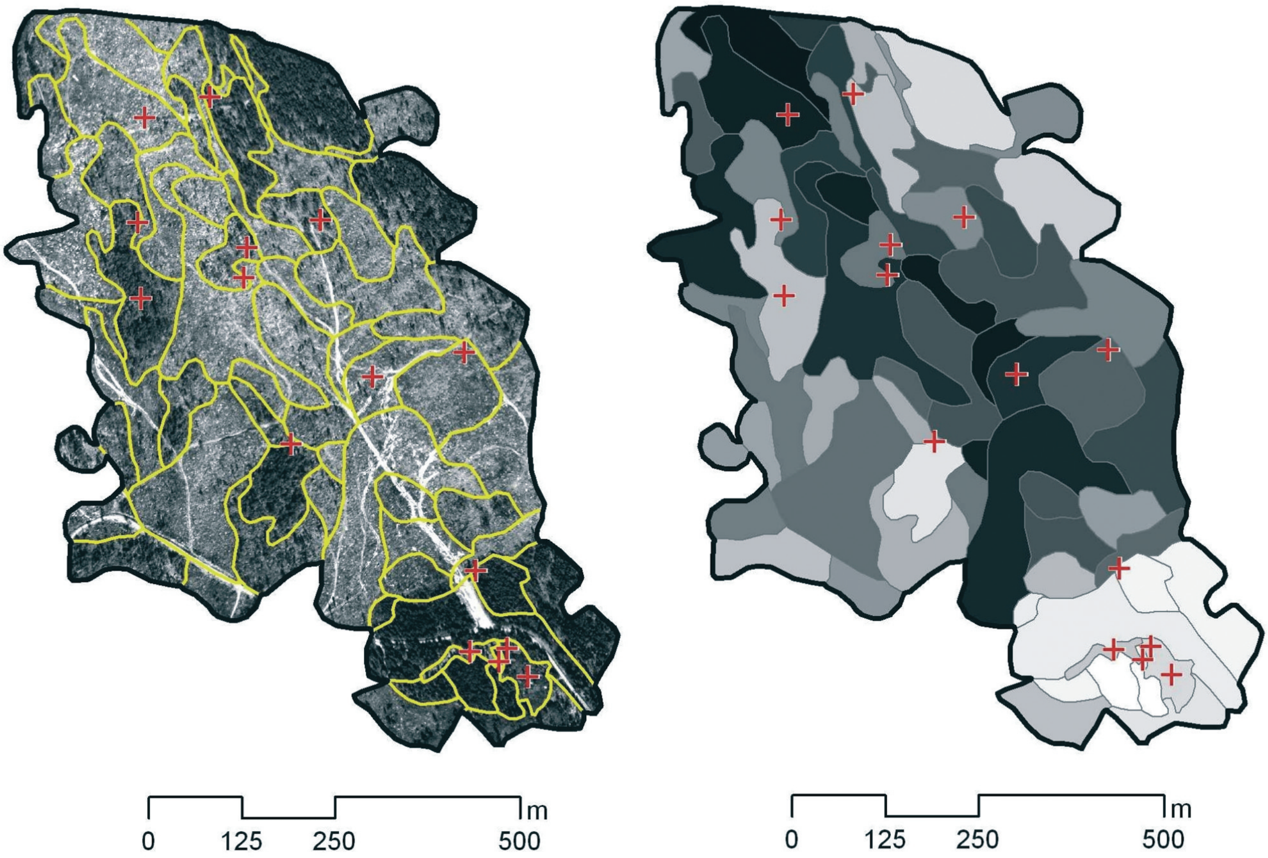

Fig. 4. Results of the relative forest damage analysis: A) Orthophotomap with selected geotops and research points, B) Relative degree of the forest damage in the geotops (dark – maximum, light – minimum)

The average values of the absolute and subsequently relative damage for the area of geotops and research were computed in ArcGIS by using map algebra (Fig. 4). Because of incompleteness of the used orthophotomap, the resultant "*Dataset of relative damage*" comprises only 108 research points. All three datasets were analysed by simple and multiple backward stepwise regression.

Moreover, some integrative indexes were computed from the primary datasets: the *wind exposition* (the angle of the probable impact of the wind),the *vertical gradients of the rock skeleton characters* (percentage, mean and maximal size), and the *site hydro-morphology* (7 ordered qualitative degrees on the basis of found underground water level, soil properties and georelief position).

Results

The main categories of geotop groups and character of their damage are listed in Tab. 1. Geotops of saddles, elevations of moraines and colluvial slopes with planted spruce growths and spruce-bilberry forests have been damaged most (about 10 percent of the tree layer coverage – E3). Small damage was recorded on geotops of erosion slopes with spruce-bilberry and fir forests (about 50 percent of the tree layer coverage), depressions and slopes of moraines covered with mixed pioneer forests (about 30 percent of the tree layer coverage).

933 slashes and 857 wind throws were recorded in all 260 tesserae (Table 1). Especially spruces have been affected by both of them. Larches seem to be more resistant. Pines have been affected less by wind throws. Trees in pioneer forests (birch, aspen, and alder) were generally less damaged. The average value of slash damage to all the entries was 3.58, and on average 3.29 trees was refuted. The average of E3 in all records was 22.72%. Overall values show large kinetic energy of wind. It is expected that displacement of the centre of gravity upward spruces in monocultures are higher damage values because of greater density than the natural spruce forests. Generally, spruces are more affected by wind throw for their shallow root system.

The least affected types of sites were fault slopes (minimum average slashes 0.2, wind throws 0.6), erosion slopes, rockfall accumulation, and moraines. It is significantly greater average damage of the trees by slashes (6.7) versus wind throws (1.9) to ridges. Overall, the most damaged site is saddle, the average density of tree layer is 8.5%, and the number of slashes and wind throws is 6.3. The S/W index

Table 1. Damage of basic types of geotops

Landform	Bedrock	Soil type	Records	Standing trees	Slashes	Wind throws	S/W	E3 (%)
Fault slope	granite	Cambic Podzols	5	16.75	0.20	0.60	0.33	54.00
Erosional slope	granite	Cambic Podzols	11	14.60	2.27	2.45	0.93	32.00
Erosional slope	granite	Sceletic Leptosols	23	12.30	3.22	2.13	1.51	30.96
Erosional-denudational slope	granite	Cambisols	17	10.53	4.35	3.35	1.30	30.07
Undistingued moraine	block granite moraine	Cambic Podzols	26	9.04	1.92	2.88	0.67	28.27
Denudational slope	granite	Cambic Podzols	11	8.90	3.91	2.54	1.54	28.09
Gentle inclined flat	granite	Cambisols	10	9.56	5.00	4.70	1.06	26.00
Steep morenic slope	block granite moraine	Cambic Podzols	35	7.29	3.29	4.04	0.81	25.29
Rockfall accumulation	granite	Lithic Leptosols	4	12.75	3.25	1.50	2.17	24.75
Glacifluvial cone	glacifluvial matherial	Cambic Podzols	8	5.13	5.38	4.38	1.23	23.06
Floodplain	fluvial holocene matherial	Fluvisols	7	13.67	3.00	3.71	0.81	22.83
Depression in moraine	till	Haplic Gleysols	14	11.07	3.36	3.29	1.02	22.21
Distinctive skeletal moraine	block granite moraine	Lithic Leptosols	7	10.14	3.14	4.57	0.69	18.86
Ridge	granite	Cambisols	7	12.00	6.71	1.86	3.61	18.59
Erosion – denudational slope	granite	Cambic Podzols	11	9.00	3.45	3.00	1.15	18.00
Depression in moraine	till	Cambic Podzols	16	8.33	2.88	4.06	0.71	16.33
Gentle morenic slope	block granite moraine	Cambic Podzols	10	4.80	4.90	3.20	1.53	14.70
Colluvial slope	granite colluvium	Cambic Podzols	21	4.76	4.76	3.66	1.30	14.00
Elevation in moraine	block granite moraine	Cambisols	13	5.46	3.85	5.54	0.69	9.77
Saddle	granite	Haplic Podzols	4	0.33	6.25	6.25	1.00	8.50

(Table 1) represents the ratio between the number of slashes and wind throws in the same type of geotops. Vegetation of ridges was damaged mostly by slashes (S/W=3.61); while fault slopes were damaged mainly by wind throws (S/W=0.33).

We studied also damage to the tree layer in dependence on chosen relevant elements of the site. Landforms exposed to the impact of wind (saddles, elevations in moraines, colluvial slopes) were significantly damaged. Little damaged trees occur in the following landforms: steep slopes (fault and erosion slopes) and protected depressions. Soil substrate had not so strong impact onto the level of damage, but generally sites with hardened bedrock were less damaged than those of crushed bedrock. We can see hydro-morphic effect of soils in this territory. First, natural vegetation on fluvisols and gleysols is relatively less harmed. Second, there is a tendency that the level of damage increases with growing soil moisture in another soil types (sequence: leptosols, cambisols, podzols).

A set of statistical tests showed a relatively weak to middle dependence between characters of absolute and relative damage and abiotic conditions. By reason of the best comparability of the absolute and relative damage, we preferred the tree layer coverage (E3) as an indicator of the forest damage.

The best results were achieved with the normalised dataset. Statistically significant relationship at the 95% confidence level were confirmed in this case with R^2 = 58.6 between the E3 and six abiotic variables (rock skeleton size, its vertical gradient and weathering, soil texture, altitude and wind exposition). Statistically significant relationship at the 99% confidence level were confirmed with R^2 = 48.4 between the E3 and three abiotic variables (percentage of the rock skeleton vertical gradient, soil texture and altitude).

The basic dataset provides also a moderate dependence, but only when the height of the trees was considered (99% confidence level, R^2 = 44.6 between the E3 and height of the trees, rock skeleton size and weathering, soil texture and georelief orientation). Pure abiotic independent variables offered only a week dependence (99% confidence level, R^2 = 27.5 between the E3 and altitude, rock skeleton size, soil texture, and georelief orientation).

The dataset of relative damage showed a little better result as the basic dataset in terms of E3 dependence (99% confidence level, R^2 = 38.3 between the E3 and altitude, rock skeleton size and georelief orientation, or $R^2 = 43.8$ between the E3 and altitude, rock skeleton size, and georelief orientation and hydromorphism). However, the dependence between the relative damage index D_R and abiotic factors was only weak (95% confidence level, $R^2 = 20.7$ between D_R and georelief orientation, soil texture and wind exposition, or $R^2 = 30.9$ between D_R and weathering and percentage of the rock skeleton, soil deep, georelief orientation, soil texture and wind exposition).

Discussion and conclusions

The presented results confirm a tendency and conclusions drawn from our previous work (Minár *et al*., 2008). Only weak to middle dependence was confirmed between characteristics of the forest damage and abiotic properties of the sites. However, a more representative dataset with normalised character of the damage characteristics improved the results and suggested that local abiotic conditions could play an important role, mainly at the boundary of a totally destroyed forest. The most important herein were the characteristics of the rock skeleton (mainly size and weathering), soil texture, georelief orientation or wind exposition. Surprisingly, the role of hydromorphism was confirmed only rarely (it can be a consequence of only approximate, qualitative character of the used index). The important role of the altitude, shown mainly in the result of normalised database, probably expresses a regional positional factor (distance from the uphill line). The geotops of saddles, elevations of moraines and colluvial slopes with planted spruce growths and spruce-bilberry forests have been damaged most. Small damage was recorded on geotops of erosion slopes with spruce-bilberry and fir forests, depressions and slopes of moraines covered with mixed pioneer forests.

Contrary to expectations, the relative forest damage index D_R did not improve the results. More factors could have contributed to this effect. First of all, only moderate dependence was confirmed between directly measured characteristics of disturbance (tree layer coverage – E3, number of staying trees) and the photogrammetrically determined absolute forest damage index D_A ($R = 0.69$ or 0.60). However, it can be a consequence of not only insufficiency of the photogrammetric method (e.g. influence of the shadows), but also of possible inaccurate field estimation of the tree layer coverage or imprecise fit of the tesserae and the measured pixel. Alternative methods of weight mean of the surroundings absolute damage could be also considered.

In line with assumption, extreme values of the least represented types of geotops in preliminary results (Minár *et al*., 2008) were reduced (Table 1). However, the spread of the geotop types (20 compared to 11 in Minár *et al*., 2008) considerably eliminated this effect.

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