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*In November 2004, the Alžbeta windstorm hit the mountainous areas of northern and central Slovakia. The most affected area was Tatra National Park, where downslope wind damaged 12,000 ha of forest, mostly Norway spruce (*Picea abies *[L.] Karst.). In the areas with the highest level of nature conservation, about 165,000 m³ of damaged wood was left uncleared. These uncleared sites triggered a serious bark beetle outbreak, where* Ips typographus *(L.) was among the dominant species. The aim of our work was to quantify and map forest damage resulting from this windstorm and subsequent insect outbreak in Tatra National Park. The objective of this article is also to present simple geographic information system (GIS) techniques available to forest managers for the detection and mapping of bark beetle infestations. The infested areas were studied using GIS and a series of color-infrared aerial photographs taken in 2005– 2009. More than 50% of all damage was recorded within 300 m, and more than 75% within 500 m, of uncleared windthrow sites. Based on our findings, we propose reinforcing post-disaster monitoring with an emphasis on (1) data acquisition and processing and (2) management of* I. typographus *outbreaks. For instance, we recommend using 300-m phytosanitary buffer zones in mountain spruce forests to prevent substantial beetle invasion from uncleared windthrow into adjacent stands.*

Keywords: *Bark beetle;* Ips typographus*; GIS; aerial photographs; windthrow; forest management; Slovakia.*

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Introduction

### Bark beetles and forests in a changing environment

Forest ecosystems worldwide are being damaged by a variety of harmful agents, resulting in destruction of individual trees and sometimes the decline of entire forest complexes (Perry et al 2008). Large-scale destruction of forest ecosystems usually results in serious economic losses (eg cessation of stands before they reach optimum wood production and deterioration of wood's technical properties) and ecological consequences (especially soil erosion, disturbed climatic conditions, and reduced biodiversity) (Seidl et al 2011). The degradation of ecological functions of forest ecosystems is a sensitive topic, especially in protected areas with a high level of nature conservation, such as national parks (Emerton et al 2006). This is strongly debated in the context of climate change and related phenomena that might have negative physiological effects on forest trees and might stimulate harmful abiotic and biotic agents (Bonan 2008; Lindner et al 2010; Hlásny et al 2014). For instance, pests such as bark beetles may become more frequent and challenging in the new environmental conditions (Beniston and Innes 1998; Kurz et al 2008; Bentz et al 2010; Sambaraju et al 2012).

Natural and meteorological disasters, including windstorms, have been increasing in the past 20 years (Birkmann and von Teichman 2010). In the case of the European spruce bark beetle, *Ips typographus* L. (Coleoptera: Curculionidae, Scolytinae), the most destructive bark beetle in the coniferous forests of the palaearctic region (Christiansen and Bakke 1988), powerful windstorms and extended periods of severe drought appear to be important triggers for outbreaks (Økland and Bjørnstad 2006). These consequences are related to the fact that physiologically weakened or mechanically damaged (broken or uprooted) trees provide suitable breeding material for *I. typographus* (Økland and Berryman 2004; Wermelinger 2004). In recent years, thousands of hectares of spruce forest have been destroyed by these insects in Europe (Wermelinger 2004; Kausrud et al 2011; Kautz et al 2011).

The current situation in Tatra National Park

Tatra National Park (TANAP) stretches across the Tatra mountain range in northern Slovakia (49°10′49″N, 19°55′10″E). The park was established in 1948 and currently extends over 73,800 ha, with 20,703 ha of protective zone. The Tatra Mountains feature 17 peaks

FIGURE 1 Study area with November 2004 windstorm damage shown in orange. (Map by Christo Nikolov and Matúš Kajba)
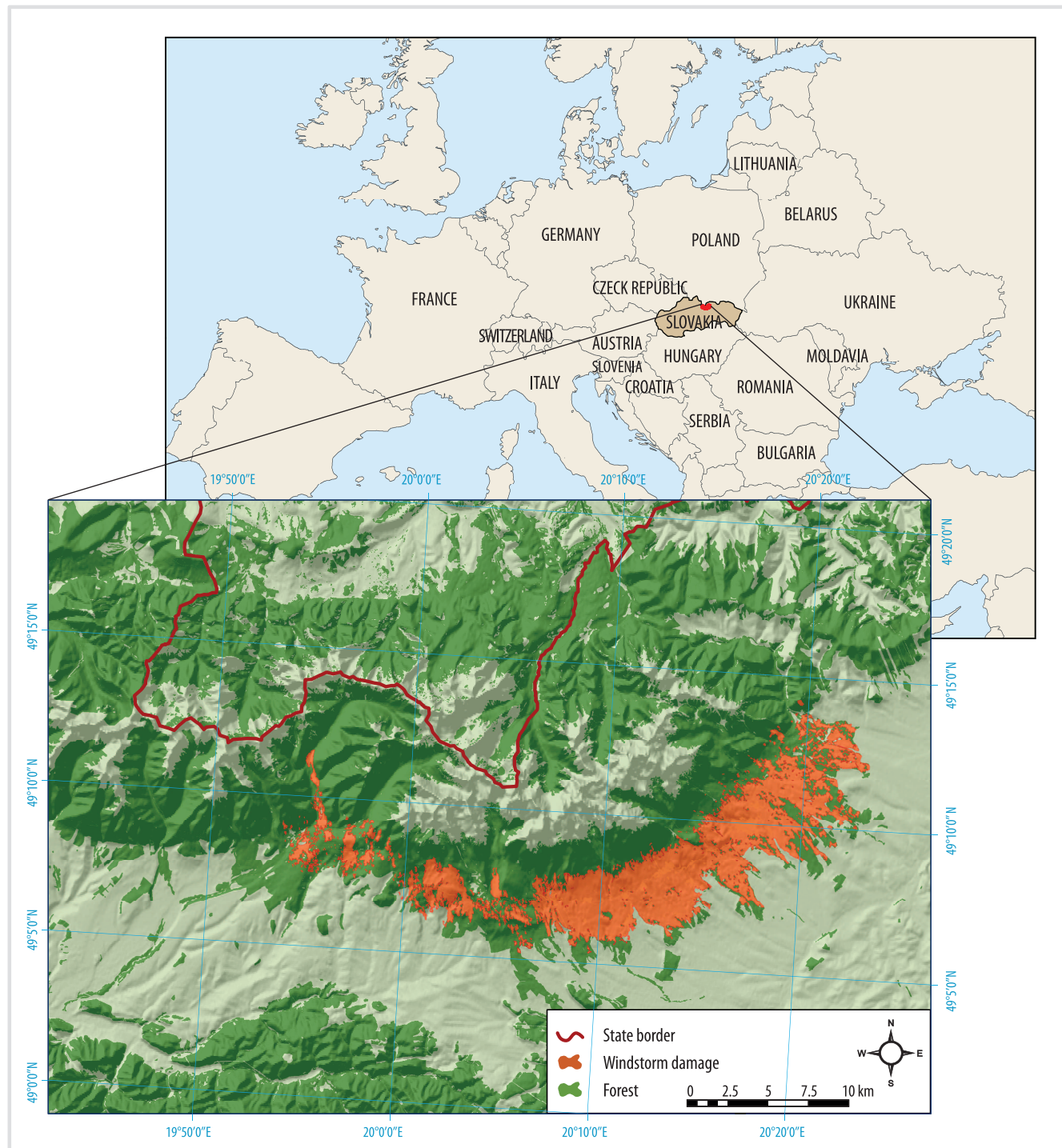
over 2,500 masl, a unique glacier relief, and the greatest number of endemic species in the Carpathian Range. Forest soils are prevailingly lithic leptosols and podzols, and bedrock is mostly granodiorite (Šály and Šurina 2007). Climate is characterized by low average

temperatures (annual mean of 5.8°C) and moderate amounts of precipitation (750 mm annually). Mean January temperature is −5.0°C, and snow cover lasts approximately 114 days a year. Summers are relatively mild, and the mean temperature in July is 14.7°C (data

FIGURE 2 Ground photos (top) and aerial infrared images (bottom) showing the extent of damage in the spruce stands in Tichá Valley in 2006 (A) and 2008 (B) and in Velická Valley in 2005 (C) and 2009 (D). Spruce trees infested by bark beetles are shown in green in the infrared images. (Photos courtesy of the TANAP Research Station)
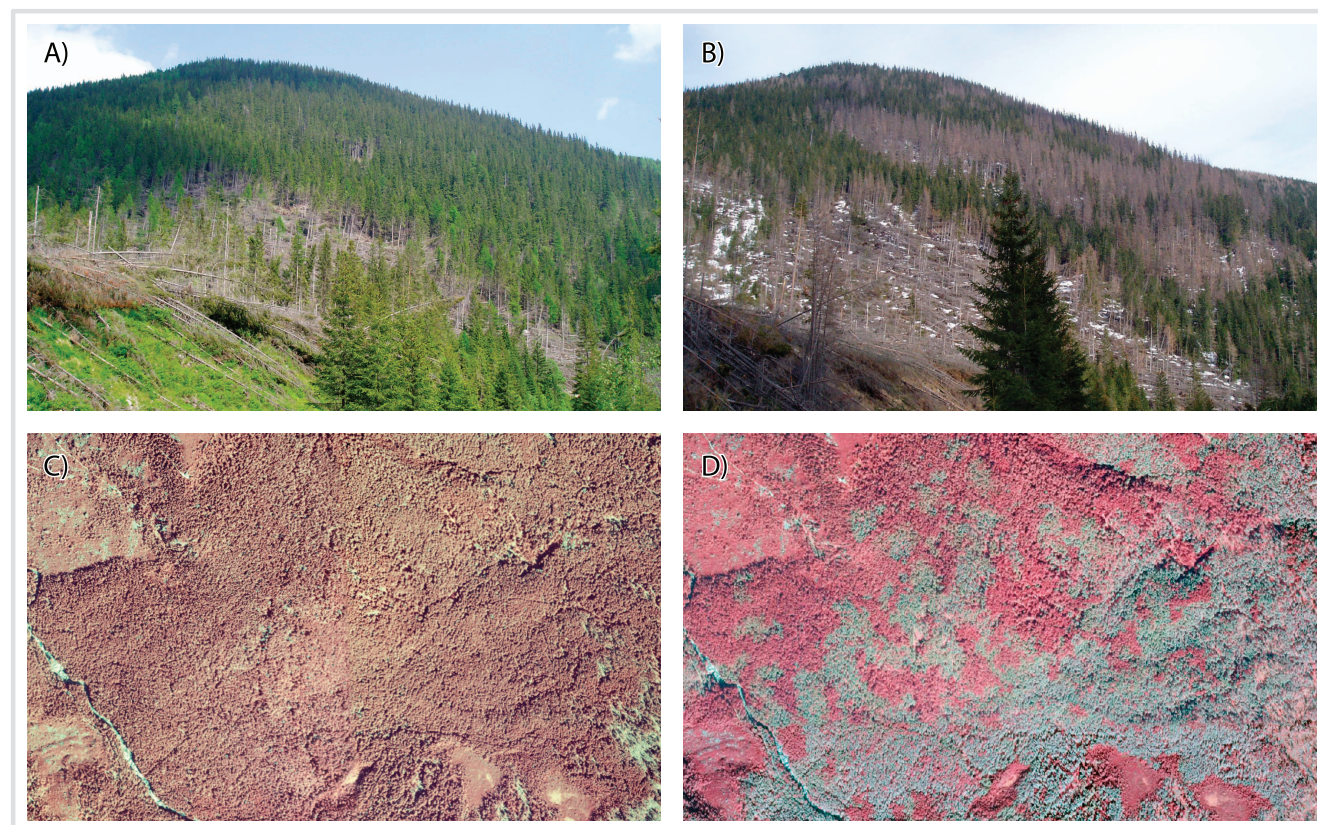
obtained from the meteorological station in Stará Lesná). The forests are dominated by Norway spruce (*Picea abies* [L.] Karst.) with European larch (*Larix decidua* Mill.), stone pine (*Pinus cembra* L.), and a few broadleaved trees as admixture species. The timberline is formed by Norway spruce, joined above by a mountain pine (*Pinus mugo*) belt (Fleischer and Homolová 2011).

On 19 November 2004, an extraordinarily strong windstorm hit the northern mountainous areas of Slovakia. In some places the wind reached a velocity of 190 km per hour. The most affected area was TANAP, where downslope wind damaged 12,000 ha of forest (Falťan et al 2011). In the areas with the highest level of protection under TANAP's forest management rules and regulations, approximately 165,000 m^3 of damaged wood was left uncleared, and the total estimated wood damage was 2.5 to 3 million cubic meters (Vakula et al 2007). These uncleared sites triggered a serious bark beetle outbreak in the study area (Nikolov 2012). The current outbreak in Slovakia is the largest and the most severe in recorded history. The total damage caused by bark beetles in 2008–2011 exceeded wind damage (Kunca et al 2012), historically the most destructive agent in Slovakia (Konôpka et al 2008). Since 2008, approximately 89% of damage and loss of Norway spruce has been caused by *I. typographus* (Kunca et al 2012).

The need for efficient monitoring of possible solutions

Precise quantification of forest damage after large-scale calamities is technically difficult if only terrestrial methods are implemented (Wulder et al 2004). This is particularly the case with bark beetle outbreaks, where forest damage is dynamic because the infestation spreads from its original location in a temporally and spatially irregular pattern. Images from remote sensing, in combination with geographic information system (GIS) tools, offer a more suitable approach (Bucha et al 2010).

The spread of the bark beetle is affected by a complex interplay between active population factors and habitat factors with varying degrees of importance (Lausch et al 2011). Susceptibility of spruce forests to bark beetle infestation is related to site and stand characteristics (Worrel 1983; Netherer and Nopp-Mayr 2005; Zolubas et al 2009), yet infestation commonly follows such events as large windstorms that trigger population growth (Christiansen and Bakke 1988; Økland and Berryman 2004). Several studies have shown that under outbreak conditions beetle infestations only spread across short distances, <500 m (eg Wichmann and Ravn 2001; Angst et al 2012). Therefore, an often recommended size of phytosanitary buffer zones around uncleared windthrow and unmanaged stands is 500 m (Wermelinger 2004; Angst et al 2012). Logging of

FIGURE 3 Development of infestation in 3 sections of spruce forest in Tatra National Park, 2005–2009, and distance zones from uncleared windthrow areas. (Map by Christo Nikolov)
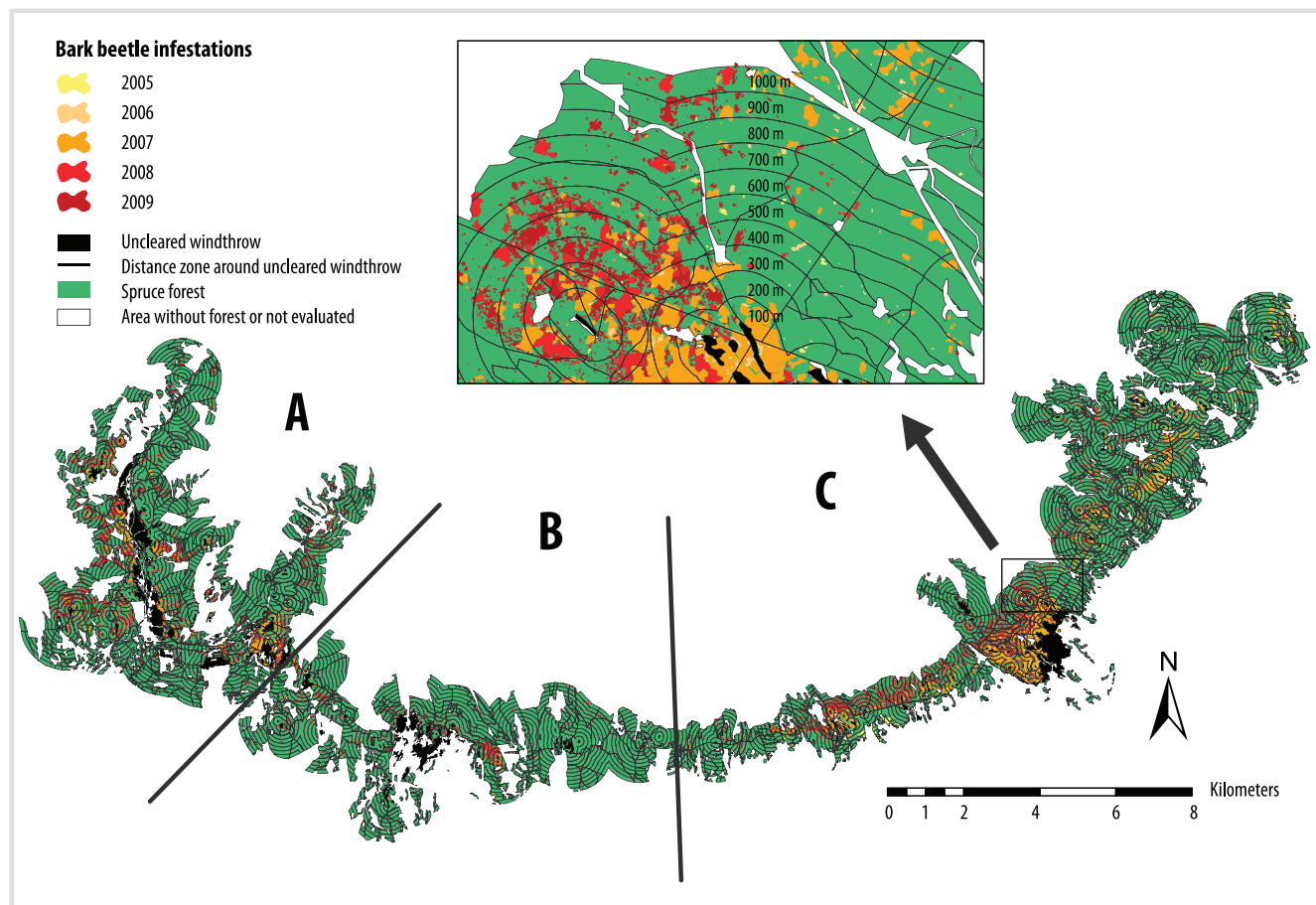
infested trees is the measure most widely used against *I. typographus* (Wermelinger 2004). Whereas most documented effects of salvage logging are negative from an ecological standpoint, others can be neutral or positive, depending on the response variables measured (Lindenmayer and Noss 2006). For example, Grodzki et al (2006) found salvage logging counterproductive, whereas Forster et al (2003) suggested that infested trees should be processed normally.

The purpose of our study was to quantify and map forest damage resulting from the November 2004 windstorm and subsequent insect outbreak in TANAP. This article also presents simple GIS techniques for detecting and mapping bark beetle infestations. Forest degradation between 2005 and 2009 was examined using a time series of aerial orthophotos and GIS. The study area covers about 39,600 ha in the central and eastern parts of TANAP, which contains dramatic topographic variation and elevation ranging from 900 to 2000 masl (Figure 1).

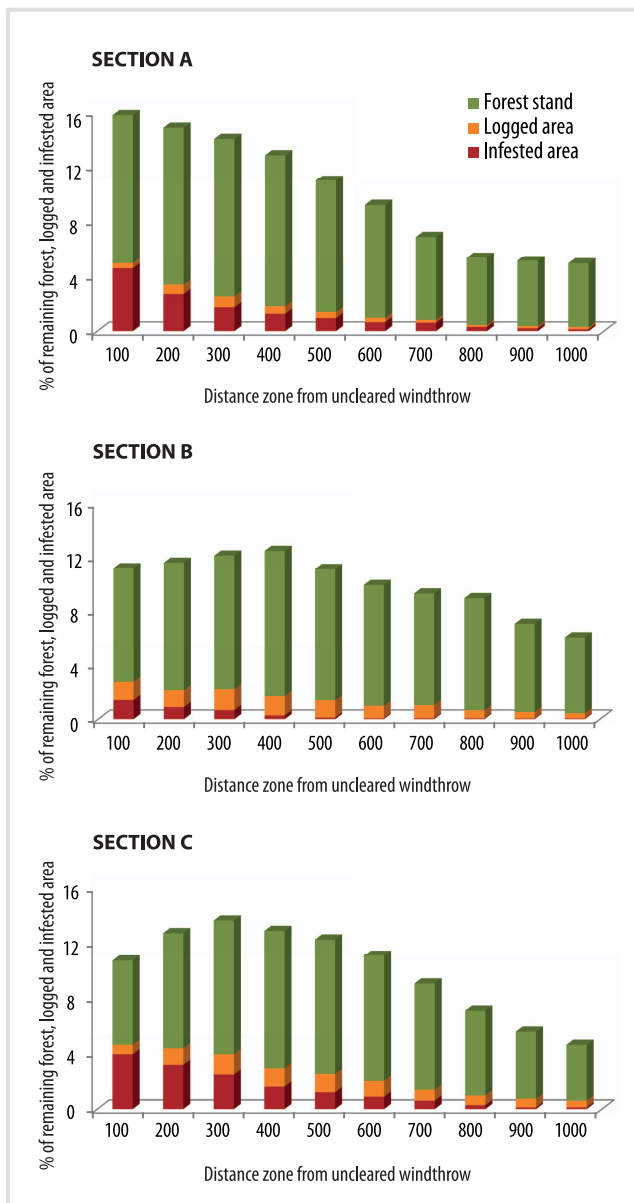### How we collected and processed the data

In the most affected part of TANAP, high-resolution aerial images in the visible and infrared spectra of

electromagnetic radiation were taken to monitor the development of forests after the disaster of 2004 (Nikolov 2012). Aerial photographs were taken once a year at the end of the growing season in late September and early October, so forest changes were examined at annual intervals between 2005 and 2009. Aerial photographs were searched for infestation patches based on the difference between red and green crowns of trees (Figure 2), which became detectable 2–4 months after infestation began.

Simple manual digitizing methods of interpretation and comparison of aerial photographs in GIS were used. Manual digitizing was chosen to ensure high accuracy of image classification. Automated classification results would have had to be visually inspected and corrected due to their expected low reliability in the extremely rugged terrain with varied light conditions (Heurich et al 2010).

Spatial layers were created, using ArcGis (ESRI) 9.2 and aerial photography, to show bark beetle infestation patches (2005–2009), logged stands (2006–2009), and uncleared windthrow areas.

Cartographic representation of infested patches captured trees mainly killed by *I. typographus*; indeed,

FIGURE 4 Percent of forest damage by year and distance from uncleared windthrow.

and potentially trigger bark beetle outbreaks (Økland and Berryman 2004; Wermelinger 2004; Eriksson et al 2005). To examine the effects of uncleared windthrows on bark beetle infestation in the study area, zones 100 meter wide around the uncleared windthrow areas up to a distance of 1000 m were created using the analysis tools in ArcGis. Distance was based on initial observations in ArcGIS, which showed that 97% of all infestations were recorded within 1000 m of an uncleared windthrow area. Spatial overlay methods were used to quantify the areas of infestation patches, logged stands, and remaining forest stand layers in each distance zone for each year. Subsequently, the percentage of damaged area and remaining forest stand as potential infestation area were calculated.

The study area was divided into 3 sections (Figure 3) based on the extent of bark beetle damage recorded in the first year of observation (2005), post-disaster management strategy, and local climatic conditions:

A   Almost no damage; limited management; colder climatic conditions than in the other 2 sections (relatively narrow valleys with shadowing from adjacent ridges); 2866 ha of spruce forest (potential infestation area) and 185 ha of uncleared windthrow;
B   No damage; intensive management; 1852 ha of spruce forest and 100 ha of uncleared windthrow;
C   Substantial damage; intensive management in the southern part of the section; 4074 ha of spruce forest and 125 ha of uncleared windthrow.

Due to its protected status, there was little logging of beetle-killed trees in section A. This action was strongly opposed by environmental organizations and some scientists. As a result, in April 2007, the Slovak Environmental Inspectorate stopped the logging 2 weeks after it started. Additional logging was conducted in 2008–2009. In June 2012, the Ministry of the Environment decided not to allow any additional logging in the Tichá and Kôprová valleys (section A) (Ministry of Environment of the Slovak Republic 2012).

Spread of *Ips typographus* in TANAP

The importance of windthrow in the initiation of *I. typographus* outbreaks has been recognized for centuries (Capecki 1986; Christiansen and Bakke 1988; Skuhravý 2002; Økland and Bjørnstad 2006). Our results confirm that uncleared windthrow areas had the greatest influence on outbreak patterns and spreading in TANAP. In all sections a remarkable decrease in damaged area was recorded with increasing distance from windthrow areas (Figure 4; Tables 1–3). Most infestations were recorded within 100 m of uncleared sites. More than 50% of total damage was observed within 300 m of windthrown stands in each section, compared with about 10% in the most distant zones (700–1000 m). Epidemic infestations only spread across distances >500 m (Wichamnn and Ravn

although forest dieback is the result of complex factors (such as fungi, drought, and emissions), in comparison with bark beetle, these agents have been found to be negligible (Kunca et al 2012). Logged stands represent trees that were cut due to an *I. typographus* infestation. This layer was created by comparing differences between 2 consecutive years. In this process, the first year of recorded logged stands was 2006. These 2 layers were considered as total damaged area in the final summary of *I. typographus* damages.

In the areas under the highest level of protection, approximately 400 ha of windthrow were left uncleared. Uncleared sites provide breeding habitat for bark beetles

TABLE 1 Forest area damaged by bark beetles according to distance from uncleared windthrow, section A.[a] (Table extended on next page)

Year	Distance from uncleared windthrow / % of total damaged area[b]					
	100 m	200 m	300 m	400 m	500 m	600 m
2005	0.07	0.03	0.02	0.01	0.01	0.00
2006	0.37	0.20	0.38	0.10	0.06	0.12
2007	**15.05**	6.18	3.13	1.43	1.08	0.79
2008	8.34	8.93	6.58	4.74	3.11	2.30
2009	5.13	5.38	5.10	4.38	3.78	2.35
Total	28.96	20.72	15.21	10.66	8.04	5.56

[a]Bold font indicates maximum values.
[b]infested and logged stands were considered as total damaged area.

2001; Angst et al 2012). About 80% of total damage was recorded within 500 m in all sections.

The largest annual bark beetle damage was recorded 4 years after the windstorm in sections A and B and 3 years after the storm in section C. After a windstorm, peak *I. typographus* population densities are commonly reached in the second summer; the peak occurs in the third summer in mountain forests (Wermelinger 2004; Kausrud et al 2011). We assume that population growth in section A was limited by the colder climate (relatively narrow valleys and shadow effect of adjacent ridges), yet the outbreak peak was only temporarily delayed, not inhibited, and beetle damage remained high until the end of study period.

The most probable cause of delay of the outbreak peak and the lower infestation level in section B was intensive management, where approximately 70% of all infested trees were cleared (Figure 4B). A simulation by Fahse and Heurich (2011) showed that an outbreak can be controlled if at least 80% of *I. typographus* specimens are killed. Effectiveness of sanitary logging in our study area was, however, difficult to evaluate. At some sites, logging was approved too late (in 2007). Areas of active forest management were intermingled with nonmanaged, infested forest. Edges of stands cleared of infestation were reinfested. It is almost impossible to determine to what degree infestations in unmanaged stands contribute to new infestations in neighboring managed stands (Forster et al 2003). Grodzki et al (2003) presumed that classical sanitary logging often leads to an increase in the attractiveness of forest edges to bark beetles. Infested trees are often discovered too late, so that most or all of the filial beetle generation has emerged, which was probably the case in the most damaged forest section (section C), which had already been affected by windthrow and subsequent bark beetle infestation in 2000 and 2002. Population densities remained high in 2005 as well.

Implications for forest management in mountain spruce forests

Our findings support the general recommendations (eg Ravn 1985; Christiansen and Bakke 1988; Mitchell 1995; Mitchell and Rodney 2001; Wichmann and Ravn 2001; Forster et al 2003; Wermelinger 2004; Baier et al 2007; Fahse and Heurich 2011; Angst et al 2012) for windthrow

TABLE 2 Forest area damaged by bark beetles according to distance from uncleared windthrow, section B.[a] (Table extended on next page)

Year	Distance from uncleared windthrow / % of total damaged area[b]					
	100 m	200 m	300 m	400 m	500 m	600 m
2005	0.00	0.00	0.00	0.00	0.00	0.00
2006	0.38	0.47	0.43	0.97	0.71	0.65
2007	2.29	2.17	2.60	2.17	2.25	1.52
2008	**9.91**	6.69	6.79	5.08	3.91	2.33
2009	7.18	6.01	5.94	4.45	3.17	2.54
Total	19.76	15.34	15.76	12.67	10.04	7.04

[a]Bold font indicates maximum values.
[b]infested and logged stands were considered as total damaged area.

TABLE 1 Extended.

Year	Distance from uncleared windthrow / % of total damaged area[b)]				Total	
	700 m	800 m	900 m	1000 m	(%)	(ha)
2005	0.00	0.00	0.00	0.00	0.14	0.71
2006	0.09	0.15	0.18	0.06	1.71	8.74
2007	0.99	0.56	0.50	0.30	30.01	153.91
2008	1.43	0.81	0.63	0.53	**37.40**	191.79
2009	2.00	0.99	0.79	0.84	30.74	157.71
Total	4.51	2.51	2.10	1.73	100.00	512.86

monitoring and management in spruce-dominated stands. We propose to reinforce post-disaster monitoring with an emphasis on 2 aspects: data acquisition and processing, and management of outbreaks.

Data acquisition and processing steps should include the following:

- *Spatial distribution of windthrows and bark beetle infestations*—Conduct aerial photography of the affected territory and its surroundings right after a windstorm. Map the extent and distribution of windthrows, which have a major impact on the further development and population dynamics of bark beetles after the disturbance. Use remote sensing data and GIS tools to map initial bark beetle infestation. Evaluate probabilities for storm damage and bark beetle infestation.
- *Stand predisposition*—Stand-related information (eg basal area, composition, stand density, diameter at breast height, and age-class) on the forest compartment layer (ie layer showing internal forest boundaries with uniform forest types; see Armitage 1998) help to evaluate the susceptibility of forest stands to bark beetle infestation in the vicinity of windthrow areas (eg Netherer and Nopp-Mayr 2005; Hilszczański et al 2006; Zolubas et al 2009).

- *Site predisposition*—Site-related parameters such as air temperature, topographic parameters (slope, aspect, and elevation), and solar radiation strongly influence bark beetle development (Worrel 1983; Jakuš et al 2003; Grodzki et al 2003, 2006; Baier et al 2007). Most of these characteristics can be derived from a digital elevation model.

Spatial analysis in GIS and the combination of created layers can be used to generate maps illustrating the hazard of bark beetle outbreaks. The suggested process is illustrated in a simplified way in Figure 5.

Management of *I. typographus* outbreaks should include the following:

- Peaks of *I. typographus* population densities in mountain forests are reached in the third summer after a windstorm. In the first 2 years after windthrow, focus on removing all damaged wood. Windfelled trees in the vicinity of infestation spots should be cleared first if possible.
- In the second stage, focus mainly on zones up to 300 m from uncleared windthrow. After a windstorm, monitoring and sanitary measures within a 300 m buffer zone in mountain forests seems sufficient. Monitoring

TABLE 2 Extended.

Year	Distance from uncleared windthrow / % of total damaged area[b)]				Total	
	700 m	800 m	900 m	1000 m	(%)	(ha)
2005	0.00	0.00	0.00	0.00	0.00	0.00
2006	0.44	0.67	0.31	0.16	5.19	13.94
2007	1.33	1.11	0.68	0.66	16.78	45.04
2008	3.26	1.60	1.54	1.18	**42.29**	113.61
2009	2.49	1.49	1.36	1.11	35.74	95.98
Total	7.52	4.87	3.89	3.11	100.00	268.57

TABLE 3 Forest area damaged by bark beetles according to distance from uncleared windthrow, section C.[a] (Table extended on next page)

Year	Distance from uncleared windthrow / % of total damaged area[b]					
	100 m	200 m	300 m	400 m	500 m	600 m
2005	0.09	0.03	0.20	0.16	0.29	0.26
2006	1.44	0.92	1.10	1.19	1.09	1.07
2007	**12.30**	8.17	6.87	4.49	3.44	2.99
2008	3.25	4.64	4.34	3.15	2.47	1.78
2009	3.05	4.44	3.91	3.07	2.95	1.91
Total	20.13	18.20	16.42	12.06	10.24	8.01

[a]Bold font indicates maximum values.

[b]infested and logged stands were considered as total damaged area.

beetle infestations in wider buffer zones is more difficult and labor-intensive because of the size of the area to be controlled.

- Create buffer zones between sites where it is impossible to remove damaged wood (due to accessibility or level of protection) and adjacent managed sites.
- In small windthrows, an *I. typographus* outbreak may be extenuated by the removal of infested trees (standing and windthrown) in the period between the spring flight and the emergence of the new generation, thereby using the windthrown trees as trap trees (Wichmann and Ravn 2001).

Conclusions

We used aerial photographs and simple GIS techniques to map the extent and distribution of windthrows and bark beetle infestations. This study shows how accurately and easily important forest changes can be documented, analyzed, and evaluated using GIS. The use of aerial photographs to visually identify infestation patches using manual vectorization is very time consuming; thus, application of this method is restricted to relatively small areas. Our analyses suggest that the exclusion or delay of post-disaster management could have adverse consequences
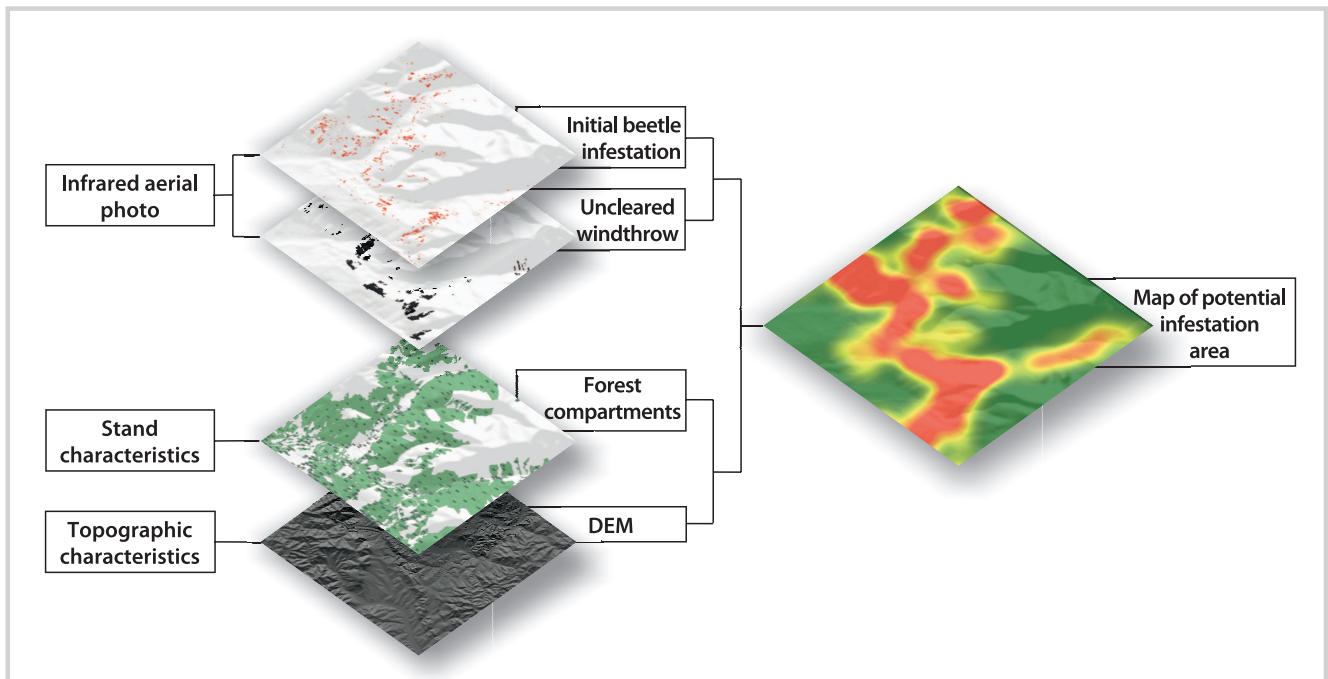
FIGURE 5 Suggested use of GIS data and data derived from aerial photos to locate areas of high risk for initial bark beetle infestation. (Design by Christo Nikolov)

TABLE 3 Extended.

Year	Distance from uncleared windthrow / % of total damaged area[b)]				Total	
	700 m	800 m	900 m	1000 m	(%)	(ha)
2005	0.04	0.03	0.00	0.00	1.10	11.94
2006	0.79	0.57	0.51	0.87	9.55	102.51
2007	2.31	1.61	1.18	0.66	**44.02**	472.47
2008	1.17	0.99	0.89	0.57	23.25	249.46
2009	1.25	0.71	0.42	0.37	22.08	236.96
Total	5.56	3.91	3.00	2.47	100.00	1073.34

for forest ecosystem stability. We believe clearing windthrows is the most effective control measure. Relatively small areas of uncleared windthrow and initial *I. typographus* infestation spots can trigger extensive bark beetle outbreaks. We suggest using 300 m phytosanitary buffer zones in mountain spruce forests to prevent substantial beetle invasion from uncleared windthrow in adjacent stands.

Lindenmayer and Noss (2006) assert that new terminology is needed. According to their work, salvage logging generally does not help regenerate or save ecosystems, communities, or species and often has the opposite effect. Therefore, the term "salvage logging" should be replaced by "postdisturbance logging." It was impossible to determine to what degree infestations in adjacent unmanaged stands contribute to new infestations, but recorded damage in section B, where 70% of infested stands were logged, was lowest.

It is difficult to draw final conclusions based on our study because an outbreak condition was still being detected at the end of the study period. The positive and negative effects of windthrow removal and salvage logging of infested trees need to be studied in more detail.

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