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Assessment of tree mortality after windthrow using photo-derived data

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We used sequential surface photography and photo-derived data to evaluate tree mortality in a windthrow area in eastern Estonia, where a storm occurred in 2001. The study is based on photographs taken from the edge of three completely destroyed areas with total canopy destruction in which wind-felled spruce trees (*Picea abies*) were left after disturbance. In total, 137 spruce trees were observed over a five-year period. We used a transition matrix to examine tree mortality dynamics and patterns. At the end of the five-year period, only 25% of the spruce trees survived in areas surrounding the windthrow. The mortality was highest in the second year after disturbance and the probability of a tree falling was surprisingly high over the entire study period. According to local observations, *Ips typographus* caused most of the tree deaths, but the co-influences of other factors were also important as there was a large proportion of falling trees in the area.

Key words: *Ips typographus,* Norway spruce, *Picea abies*, repeat photography, transition matrix, windthrow

Introduction

Windstorms with windthrows play an important role in the successional cycle and dynamics of natural forests (Bouget & Duelli 2004). Windthrow increases the regional proportion of early successional and edge habitats as well as patchy open areas (Bouget & Duelli 2004). The intensity of disturbance leads to different types of opening, ranging from tree-fall gaps to stand-replacing areas. By damaging trees around larger windthrow areas and smaller gaps, windstorms even create dead-wood habitats on standing living trees, like dead branches, decaying cores and cavities (Bouget & Duelli 2004). Changes in abundance and in distribution patterns of dead wood as resources affect the abundance of insect species. Wind-felled Norway spruce (*Picea abies*) offer breeding ground for a wide range of insects and pests (Eriksson *et al*. 2005) which, in case of more severe windstorms, may lead to a population outbreak and subsequent attacks on living spruce (Schroeder 2001).

It is well known that large-scale outbreaks of the spruce bark beetle (*Ips typographus*) will develop when large numbers of fallen spruce trees are left in the forests after storms or other disturbances (Peltonen 1999, Göthlin *et al*. 2000, Nageleisen 2001, Hedgren *et al*. 2003, Meier *et al*. 2003, Okland & Berryman 2004). Generally *I. typographus* prefers to reproduce in wind-felled or otherwise damaged trees, but in some cases it is also able to damage and kill living trees in large numbers (Schroeder 2001). Several severe outbreaks are known from historical records (Schelhaas *et al*. 2003, Skuhravy 2004). Salvage logging or retention of wind-felled trees and the risk of consequential tree mortality is an important problem for forestry practice (Duelli & Obrist 1999, Wichmann & Ravn 2001, Eriksson *et al*. 2007). Due to logistical, economical and ecological reasons more and more suitable breeding material and infested trees will remain in the stands which results in increasing populations of bark beetles and their influences on standing trees (Forster 2006).

Landscape photography from a single location is used to view the typical landscape features under different environmental conditions (Dahdouh-Guebas & Koedam 2008). Some scientists have used sequential photographs to research ecosystem vegetation changes (Moseley 2006). Various methods have been used to estimate numbers of weakened, damaged or killed trees. In North America a sequential aerial photography method was used to detect trees killed by bark beetles (DeMars *et al*. 1980). Panoramic photography has been used to estimate bark beetle-killed or drought-stressed trees and to investigate other forest damage types (Caylor *et al*. 1982, Ciesla *et al*. 1982, Dillman & White 1982, Klein 1982). Recently roadside sampling was used to assess bark-beetle damage in France (Samalens *et al*. 2007).

Conventional methods such as sample plots or line transects for estimation of tree mortality in storm-disturbed areas are time consuming. Aerial surveys or mapping bark beetle infestation with high spatial resolution satellite imagery are also complicated.

In this study, we used a simple method for assessment of mortality of standing trees at the edge of heavily disturbed forest area — sequential surface photography and photo-derived data combined with local observations. Repeat photography of identical forest views is a quick and effective method for documenting changes. The key to the success of photo monitoring lies in accurately recording each step in the process and recreating the identical set up in the future (Hall 2001).

The main objective of this study was to evaluate tree mortality after windthrow. We hypothesized that weakened trees can recover to some extent during the period of observation.

Material and methods

The study areas were situated in eastern Estonia, in the Tudu Forest district (59°11´N, 26°52´E), which experienced storms on 16 July 2001. The areas are situated in the hemiboreal vegetation zone (Ahti *et al*. 1968), Norway spruce (*Picea abies*) being the dominant tree species. European aspen (*Populus tremula*), black alder (*Alnus glutinosa*), silver birch (*Betula pendula*), downy birch (*Betula pubescens*) and rowan (*Sorbus aucuparia*) were secondary tree species. The study areas included stands on eutric gleysols and calcaric cambisols (Reintam *et al*. 2001), *Filipendula* and *Myrtillus* forest site types (Lõhmus 1984) being most commonly represented (Ilisson *et al*. 2005, 2007, Köster *et al*. 2007).

No salvage logging occurred between windfall and measurements. Fieldwork was conducted in 2002, 2003, 2004, 2005 and 2006. The forest was previously under protection and no intensive management had been carried out in the area for decades. The stand ages ranged from 110 to 160 years.

The study was based on photographs taken from three completely damaged areas with total canopy destruction (all trees damaged by storm) that was the part of a larger study area. Detailed description of how the study sites where chosen has been published elsewhere (Ilisson *et al*. 2005, 2007, Köster *et al*. 2007) and the pictures used in this study are the outcome of a more extensive study program.

A Nikon D50 digital single-lens reflex camera with a 6.1 million-pixel element was used to capture the images. The camera location and photo point remained the same, as we used permanent markers for that purpose. The focal

Fig. 1. Pictures from study plot no. 5, taken in 2002 and 2005.

length was set at 18 mm to capture the maximum field of view of the plot and remained the same for all subsequent pictures. The camera was set to "Auto" to allow for automatic adjustment of aperture and shutter speed. The first picture was taken at the end of January in winter 2002, six months after the disturbance. This photo image is regarded as the initial stage of measurements. The other pictures were taken in the autumns (September–October) of 2003, 2004, 2005 and 2006. Local observations were carried out to visually determine the causes of mortality.

In the first picture, we numbered every spruce that we could distinguish on the scope and later verified what changes took place in the subsequent years (Fig. 1). Multiple observers worked with first picture untill they all got the same tree count. Every year we placed each tree into one of four classes (Table 1): living tree = tree shape and crown not damaged; standing dead tree = with no needles detected; damaged tree = at least 25% decrease in crown density; fallen tree = disappeared from picture. In total 137 spruce trees were observed during the five-year period.

Table 1. Data collected from three completely damaged areas with total canopy destruction in different years.

		Number (percentage) of trees				
Plot	Year	Living	Standing dead	Damaged	Fallen	Total
1	2002	46 (82.1)	8 (14.3)	2 (3.6)	0 (0)	56
	2003	15 (26.8)	24 (42.9)	15 (26.8)	2 (3.6)	56
	2004	15 (26.8)	27 (48.2)	6 (10.7)	8 (14.3)	56
	2005	17 (30.4)	22 (39.3)	3 (5.4)	14 (25.0)	56
	2006	17 (30.4)	18 (32.1)	2 (3.6)	19 (33.9)	56
5	2002	46 (93.9)	1 (2.0)	2 (4.1)	0 (0)	49
	2003	16 (32.7)	18 (36.7)	11 (22.4)	4 (8.2)	49
	2004	19 (38.8)	22 (44.9)	4 (8.2)	4 (8.2)	49
	2005	17 (34.7)	22 (44.9)	2 (4.1)	8 (16.3)	49
	2006	14 (28.6)	21 (42.9)	0 (0)	14 (28.6)	49
9	2002	13 (40.6)	18 (56.3)	1 (3.1)	0 (0)	32
	2003	7 (21.9)	16 (50.0)	5 (15.6)	4 (12.5)	32
	2004	5 (15.6)	21 (65.6)	0 (0)	6 (18.8)	32
	2005	4 (12.5)	12 (37.5)	0 (0)	16 (50.0)	32
	2006	3 (9.4)	11 (34.4)	1 (3.1)	17 (53.1)	32

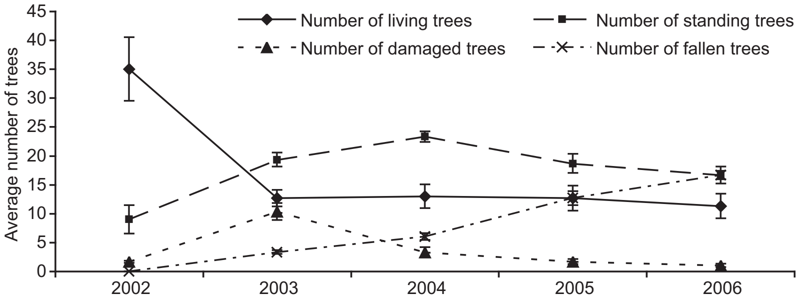

Fig. 2. Changes in average number of trees from sample plots in four different classes per year.

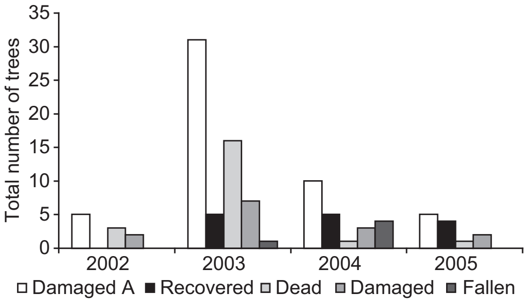

Fig. 3. Changes within damaged trees in different years after disturbance, where Damaged A represents the number of damaged trees at the beginning of the study year and other columns show the changes in those damaged trees during the year.

We used a transition matrix (Eq. 1) to determine the probabilities with which trees in different classes moved to another class. The probabilities were arranged so that the columns represented transitions from each tree state class initially present at a specific class, while the rows represented transitions to each class one time interval later. This matrix was then of the form:

$$\mathbf{A} = \begin{pmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1n} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2n} \\ p_{31} & p_{32} & p_{33} & \cdots & p_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{n1} & p_{n2} & p_{n3} & \cdots & p_{nn} \end{pmatrix} \quad (1)$$

where p_{1n} was the probability of transition to class 1 from n time intervals. Multiplication of this matrix, $\mathbf{A}$, by a column vector $\boldsymbol{x}_t$ that describes the tree state class at time t gives the tree state class at time $t + 1$.

We also used the chi-square (χ^2) test to see if the transition matrices were statistically different in different years.

Results

The results of this study allowed us to predict five-year dynamics after disturbance. During this period, approximately 25% of the spruces survived in areas surrounding the windthrow (not totally damaged by storm). On average, only 11 trees per plot out of 35 survived (Fig. 2). We found the largest number of damaged trees (more than 22% on average) in the second year after disturbance (Table 1 and Fig. 2). The number of damaged trees started to decrease later and, while most of those trees died, some recovered and continued as living trees (Fig. 3). The transition probability matrix demonstrated that most of the damaged trees died during the second year after disturbance, but some recovered (Table 2 and Fig. 3). After a longer time after the disturbance — in the third and fourth years — the relative number of trees recovering was remarkably high (more than 50% of the damaged trees recovered; Fig. 3).

The number of standing dead trees increased until the third year after disturbance (Fig. 2). The number of standing dead trees later decreased, as these were starting to fall. It can be suggested that the probability of a standing dead tree falling down was greatest at the end of the fourth year, but in general a considerable number of standing dead trees fell each year (Table 2).

The most rapid change in the number of living trees took place during the second year after disturbance (Figs. 2 and 4), but this number remained stable later. During those rapid changes in the number of living trees, most trees were damaged or already standing dead trees, but some living trees fell as well (Fig 4).

Some interesting patterns emerged from examination of the transition matrices (Table 2).

A remarkably high recovery of damaged trees was observed every year. The probability of a tree falling was surprisingly high during the entire five-year study period.

Discussion

The results of our study followed the same pattern as reported in earlier papers, in which the mortality in the areas studied was highest in the second or third summer following the storm disturbance (Schroeder 2001, Bouget & Duelli 2004, Eriksson *et al*. 2007). In our study, almost half of the tree deaths were recorded in the second year following the wind felling. These tree deaths were probably caused by *I. typographus*, as it came out from local observations that all the dead spruce trees were colonized by it, although the analysis of sequential photographs is often limited to visual inspection and it is hard to determine the exact cause of tree death.

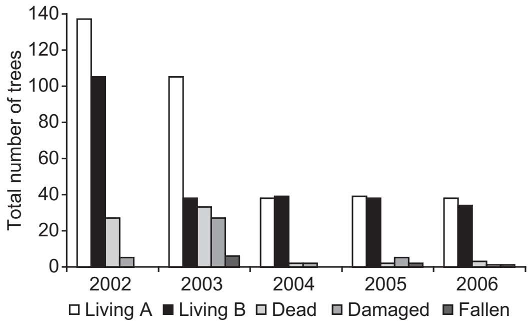

Fig. 4. Changes within living trees in different years after disturbance, where Living A represents the number of living trees at the beginning of the study year and other columns represent the changes in those living trees during the year.

About 1.5 million m^3 of wood was damaged by local windstorms in 2001 and 2002, but as timber was removed in time, no extensive outbreaks of bark beetles in the commercial forests followed. However, quite a different situation was observed in the protected forests of nature reserves, where the storm-damaged trees were

Table 2. Transition probability matrices. The columns represent transitions from each class initially at time *t*, while the rows represent transitions to each class one time interval later ($t + 1$). Differences between matrices were tested with a χ^2-test.

	Trees			
	Living	Damaged	Fallen	Standing dead
Number of trees in 2002	105	5	0	27
2002–2003 $p < 0.0001$				
Living	0.277	0.000	0.000	0.000
Damaged	0.204	0.015	0.000	0.000
Fallen	0.044	0.000	0.000	0.036
Standing dead	0.241	0.022	0.000	0.161
2003–2004 $p < 0.0001$				
Living	0.248	0.036	0.000	0.000
Damaged	0.015	0.058	0.000	0.000
Fallen	0.000	0.007	0.073	0.007
Standing dead	0.015	0.117	0.007	0.372
2004–2005 $p < 0.0001$				
Living	0.219	0.036	0.000	0.000
Damaged	0.036	0.022	0.000	0.000
Fallen	0.015	0.007	0.131	0.124
Standing dead	0.015	0.007	0.000	0.387
2005–2006 $p < 0.0001$				
Living	0.219	0.036	0.000	0.000
Damaged	0.007	0.015	0.000	0.000
Fallen	0.007	0.000	0.277	0.073
Standing dead	0.022	0.007	0.000	0.336

left untouched. This led to an increase in the bark beetle populations and resulted in extensive beetle-induced tree mortality in neighbouring spruce stands. Damage by spruce bark beetles occurs mainly in eastern Estonia (Nilson *et al.* 1999), where spruce stands grow in site types where soil humidity depends directly on the amount of precipitation. Some studies found that in very hot summers, as in 2001 and 2002, *I. typographus* prefers the cooler inner parts of the stands for breeding rather than sun-exposed open habitats (Eriksson *et al.* 2007). Bark beetles generally prefer wind-felled or otherwise damaged spruce trees (Schroeder 2001, Eriksson *et al.* 2007), but most wind-felled trees become unsuitable as breeding-ground a year or two after disturbance (Bouget & Duelli 2004) and bark beetles are confined to attacking living trees on the surrounding edges (Peltonen 1999, Schroeder 2001). The list of bark beetles of Estonia includes 68 species (Voolma *et al.* 2000), but only a few can attack growing trees and pose a real threat to forests. Bark beetles of the *Ips* genus belong to those that can affect forests most. Of the five species of this genus occurring in Estonia, three (*Ips typographus*, *I. duplicatus*, *I. amitinus*) inhabit Norway spruce. All these species, as well as an accompanying species, *Pityogenes chalcographus*, were recorded in the study area when the local observation was carried out.

The probability of a dead standing tree falling and for a living tree falling was surprisingly high during the entire five-year study period. This quite early falling of standing dead trees made it seem that not all spruces were killed by bark beetles. Here we can probably consider the co-influence of various disturbance types. The root systems of living spruces were probably damaged by storms or fungi, thus weakening the trees. Bark beetles killed the trees and these standing dead spruces fell so early because of their damaged root system. It usually takes some decades for standing dead trees to fall because of decomposition (Storaunet & Rolstad 2002, 2004, Storaunet 2004), mainly because of drying out after death (Krankina & Harmon 1995). The same pattern was also observed in our storm-damaged areas (stands totally and partially damaged by wind) where broken spruce stems are still standing (K. Köster unpubl. data). Therefore, we assume that trees survived the storm, but that their root systems were damaged, weakening them. The co-influence of storm damage and bark beetle attacks made the trees die quickly and they blew down with the next strong winds. The repeated storm events cause complex patterns of tree mortality. Eriksson *et al.* (2007) found that older standing trees seem to be more susceptible to *I. typograpus* attacks than younger ones. In our study, the stand ages ranged from 110 to 160 years, and this may also be a factor causing high mortality among trees that survived the wind damage.

Seasonal aspects are also important. The time of year when trees are windthrown also influences the level of colonization by beetles (Bouget & Duelli 2004, Eriksson *et al.* 2007). Trees falling in winter provide less decay products attractive to beetles than trees falling in autumn (Schroeder *et al.* 1999). The winter conditions with frozen ground also reduce the risk of damage to roots.

It is possible that other factors besides partial damage and associated bark beetle attacks are responsible for tree death. An altered water regime or temperature fluctuations in open conditions may increase susceptibility to bark beetle attacks or infection by fungi (Harmon *et al.* 1986, Storaunet & Rolstad 2002, 2004, Storaunet 2004).

Management decisions are crucial in planning forests. Salvage logging is a decision often made by managers after disturbance because of the fear of insect outbreaks and fire hazard (Stanturf *et al.* 2007). The question of salvaging partially damaged areas is also unanswered. With heavy destruction, the problem of the surviving trees remains. We may also imagine that if the border between damaged and surviving stands is strict, it might mean that the survival of an undamaged stand is better since they are in good condition. In a situation where we have a half-damaged area between damaged and surviving stands, however, it might be a good idea to remove the half-damaged stand.

Wichmann and Ravn (2001) observed that the density of attacks on standing trees around windthrown trees correlates with the time of salvage harvesting. Removal of fallen trees before the first spring may further inhibit local infestations. In this case, living trees are used as bait trees, since they are attractive to the hibernating beetles and natural enemies of beetles emerge from spruce logs one or two months after the spruce bark beetles (Wermelinger 2002). Foresters should thus focus on sanitation fellings of newly-attacked living trees and leave the older stems and standing dead trees for the benefit of saproxylics and natural enemies (Wermelinger 2002). On the other hand, the decision to leave a part unsalvaged may be essential to protect other resource values (Stanturf *et al*. 2007). Areas with regeneration due to excessive game browsing may benefit from coarse woody debris created after a storm (de Chantal & Granström 2007) or its delayed formation.

Monitoring of bark-beetle damage is often problematic and efforts are being made to estimate damage extent more extensively and precisely. Many large-scale outbreaks of spruce bark beetles have been reported in Estonia over the last two centuries, in 1868–1874, 1880–1886, 1897–1902, 1912–1915, 1924–1929, 1934–1940, 1968–1973, and 1992–1995 (Voolma 1998, Voolma *et al*. 2000, Wichmann & Ravn 2001, Voolma 2002). Various natural disturbances in forests have usually preceded the outbreaks: a hot summer and big forest fires in 1868, snow breaks in 1879–1880 and 1911, storm damage in 1923, 1938, 1943, 1967 and 1969, and drought in 1882, 1934–1935 and 1992. The heaviest storm in Estonia occurred in August 1967, devastating about 6 million m^3 of forest, with trees downed and uprooted along the storm path. The ensuing damage caused by bark beetles exceeded 2 million m^3 (Mihkelson 1998). Since some countries now have the goal of retaining biodiversity by leaving more and more wind-felled trees in the managed forest (Schroeder 2001), it is important to evaluate the risk of damage caused by the wind, bark beetles and other factors, and repeat photography definitely qualifies as a cheap and accessible data source.

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