Large-scale risk mapping of an eruptive bark beetle – Importance of forest susceptibility and beetle pressure

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ABSTRACT

Bark beetle outbreaks have increased in Europe and North America. To mitigate damage efficiently during outbreaks, robust models predicting where the risk for tree mortality is highest across forest landscapes and better understanding of the underlying mechanisms are required.

Using Boosted Regression Trees, we modelled relative risks of infestation by the spruce bark beetle *Ips typographus* (L.) across a 130,000 ha managed lowland forest landscape in southern Sweden during three years of an outbreak and at a resolution of 100×100 m. A second nearby landscape of similar size was used for validation. Both predictors reflecting forest susceptibility and beetle pressure were used. Forest susceptibility predictors included volume per ha of host and non-host trees, tree height and distance to the nearest clear-cut harvested during the last four years, all based on interpretations of satellite images. Bark beetle predictors were based on locations and sizes of previous year infestation spots recorded by helicopter.

Model outcomes were similar across years, and there was no major reduction in performance when extrapolating predictions in space or time, indicating the modelled relationships have high reliability. Area under curve (AUC) values varied from 0.729 to 0.818. Including bark beetle predictors increased the AUC value somewhat in one of two years.

The most important predictor was volume per ha of the host tree, Norway spruce *Picea abies* (L.) Karst., which reflects the probability of bark beetles encountering suitable trees. This variable was strongly positively correlated with risk up to 200 m^3 ha^{-1}. Unexpectedly, the volume of the non-host birch was also positively correlated with infestation risk up to 25 m^3 ha^{-1}. Tree height was associated with increased infestation risk above heights of 10 m in 2008 and 15 m in 2009. In 2007 and 2008 there was a weak negative relationship between infestation risk and distance to the nearest clear-cut. Additionally, our study shows that in managed forest landscapes the *I. typographus*-killed trees are distributed in many small infestation spots spread out over the landscape.

We demonstrate that high-resolution risk-rating maps can be successfully created for large landscapes using easily accessible satellite data of forest characteristics and aerial surveys of infestation spots. The distribution of killed trees in many small infestation spots, poses a challenge for the forest owners to find and remove colonized trees before the new generation emerge. Our results suggest that mitigation efforts in managed lowland forest should focus on high volume spruce stands.

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1. Introduction

Tree-killing bark beetles cause severe damage to forests in Europe (Christiansen and Bakke, 1988) and North America (Raffa et al., 2008), resulting in large financial losses and changes in forest structure and species composition. Furthermore, the magnitude of bark beetle outbreaks has increased in recent years (Schelhaas et al., 2003; Dobbertin et al., 2007; Raffa et al., 2008; Seidl et al., 2011) and is expected to increase further with climate changes (Williams and Liebhold, 2002; Jönsson et al., 2007; Bentz et al., 2010).

To overcome tree defences, the density of attacking bark beetles needs to exceed a threshold value (Raffa and Berryman, 1983; Berryman, 1999). In accordance with this the risk of tree mortality

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caused by *I. typographus* is generally highest close to sites hosting large beetle populations (Wichmann and Ravn, 2001; Kautz et al., 2011). Killed trees are generally distributed in spatially well-defined groups, known as infestation spots (Ayres et al., 2011; Colombari et al., 2013). Apart from beetle pressure (defined as an estimate of local *I. typographus* density based on the size and proximity of infestation spots from the previous year), also several characteristics of individual trees and forest stands affect their susceptibility to beetle attack and tree mortality (Fettig et al., 2007), including variables such as stand density, age and composition (Coulson, 1979; Shore and Safranyik, 1992).

From a management perspective, timely identification of sites at most risk of tree mortality during outbreaks is a challenge. Thus, development of robust risk-rating models and maps could help managers to prioritize stands in which to apply preventive and mitigation measures. As the short-term risk of a bark beetle infestation in a given stand is a function of both forest susceptibility and beetle pressure, risk-rating models should ideally include predictors reflecting both of these elements (Bentz et al., 1993). The predictors should also be variables that can be conveniently estimated across large forest areas to be operationally useful. We aimed to fulfil these criteria for modelling and mapping the relative risk of infestation by the European spruce bark beetle *Ips typographus* (L.), across a 130,000 ha managed forest landscape in southern Sweden during three years of an outbreak.

Most previous risk-rating modelling studies of *I. typographus* are based on either stand or site characteristics (e.g. Netherer and Nopp-Mayr, 2005; Klopcic et al., 2009; Overbeck and Schmidt, 2012), or beetle pressure (Wichmann and Ravn, 2001; Kautz et al., 2011). Only two earlier studies include both stand susceptibility and beetle pressure (Lausch et al., 2011; Stadelmann et al., 2013). Our study differs in several respects from these two earlier studies. Both previous studies include both outbreak and non-outbreak periods while our study only includes outbreak conditions. The study by Stadelmann et al. (2013) was conducted at a much larger scale with forest districts as observational units (size 200–18 977 ha) and the response variable being density of *I. typographus* infestation spots per district in the next year while our study aimed to estimate the relative risk of having at least one infestation spot in 100 × 100 m cells across a forest landscape. Most of the earlier studies have been conducted in mountainous areas with large variations between sites in solar radiation and temperature sums, variables that also were important in their models, while our study was conducted in lowland conditions which are prevailing for much of Scandinavian forests.

The objectives of the present study were: (i) to develop risk-rating models for *I. typographus* based on both forest susceptibility and bark beetle pressure predictors available for large forest areas, (ii) to evaluate the relative contribution of each predictor in the models, (iii) to determine the form of relationship between the predictors and the response variable over the value range of the predictors, and (iv) to use the models to create risk-rating maps. To meet these objectives we used Boosted Regression Trees.

2. Methods

2.1. Ips typographus

Ips typographus is the most economically important tree-killing bark beetle in Europe (Grégoire and Evans, 2004). The biology of *I. typographus* has been described in detail (Christiansen and Bakke, 1988; Wermelinger, 2004). Its host tree is Norway spruce *Picea abies* (L.) Karst and in Sweden it is generally univoltine, but parent beetles may re-emerge and establish a second brood in the same season. The adults hibernate under the bark of brood trees or in

forest litter nearby. Thus, infestation spots from the previous year constitute local sources of beetles during the spring flight. At endemic population levels *I. typographus* reproduces in wind-felled or otherwise weakened trees. Storm disturbances and drought periods may trigger large-scale outbreaks as a result of the sudden surplus of breeding material with weakened, or no, defenses (Schroeder and Lindelöw, 2002; Komonen et al., 2011; Marini et al., 2013). Such an event occurred in January 2005 when the storm "Gudrun" felled 70 million m^3 of spruce in southern Sweden (Svensson, 2007). This triggered an *I. typographus* outbreak that resulted in losses of 3.2 million m^3 of spruce during the following four years (Kärvemo and Schroeder, 2010).

2.2. Study areas

The study was conducted in the province of Småland in southern Sweden from 2007 to 2009. The dominant tree species in this region are Norway spruce and Scots pine, *Pinus sylvestris* (L.). More than 95% of the forest land is managed, consisting of even-aged stands that are thinned three or four times before final harvest by clear-cutting at the age of about 80 years.

Two areas were chosen for the study: one used for building the models (hereafter the study area) and the other for external validation (the validation area). The study area covered 129,793 ha and the validation area 129,000 ha. The minimum distance between them was 1.5 km and they were very similar in terms of elevation, forest variables, soil type and number of *I. typographus* infestation spots (Table 1).

2.3. Response variable and predictors

The response variable was defined as the risk of at least one *I. typographus* infestation spot, consisting of at least five killed trees, occurring in a one ha grid cell (100 × 100 m). The predictors included four forest susceptibility variables (hereafter forest predictors), and two variables reflecting beetle pressure (bark beetle predictors). The forest predictors were: (i) volume of spruce (the host) per ha, (ii) volume of birch (non-host) per ha, (iii) mean tree height (including all tree species) and (iv) distance to the nearest recent clear-cut (i.e. harvested during the last four years). Data for the first three variables were accessed from the 2005-kNN maps of forest land in Sweden (Reese et al., 2003), which are derived from satellite images (Landsat ETM) and data recorded on the ground by the Swedish National Forest Inventory, packaged as raster layers with 25 × 25-m resolution aggregated to 100 × 100 m by averaging. The fourth variable was based on GIS-layers reflecting clear-cuts (interpretations of satellite images conducted by the Swedish Forest Agency) within the preceding four years respectively. As trees in newly-exposed stand edges (facing fresh clear-cuts) experience an increased risk of being wind-felled and subsequently colonized by *I. typographus*, such stand edges may harbour local sources of beetles (which were not recorded by the helicopter survey). These GIS-layers were also used to stepwise erase (set to "no data") annual harvested pixels from the forest layers.

The bark beetle predictors were: (i) presence/absence of *I. typographus* infestation spots during the previous year within each pixel (hereafter local infestation) and (ii) a variable summing the number of infestation spots in the neighbourhood in the previous year, weighted by spot size and distance (hereafter neighbouring infestation). The local infestation predictor reflects the increased risk for formation of infestation spots in localities with spots from the previous year (Hedgren et al., 2003). The neighbouring infestation predictor takes into account the sources of beetles in the adjacent landscape (Wichmann and Ravn, 2001; Kautz et al., 2011). The distance weighting was applied by using a

Table 1

Forest and site data, and number of *I. typographus* infestation spots (groups of ⩾5 killed spruce trees) recorded by the helicopter surveys in the study and validation areas.

	Study area			Validation area		
	Value	SD	No pixels	Value	SD	No pixels
Spruce volume, $m^3\ ha^{-1}$ (mean)	104.5	69.6	101,027	112.3	68.5	103,147
Birch volume, $m^3\ ha^{-1}$ (mean)	21.1	10.7	100,620	10.1	8.9	93,193
Tree height, m (mean)	14.7	4.8	100,931	14.6	4.7	103,007
Elevation, m (mean)	165.5	19.5	101,027	212.3	26.2	102,948
Soil type: fluvio-glacial till (% of area)	70		84,404	83		79,605
Infestation spots in 2007 (number)	1293			1998		
Infestation spots in 2008 (number)	2009			1210		
Infestation spots in 2009 (number)	1698			NA		

Gaussian moving average filter, with the radii of the moving windows corresponding to 99% of the Gaussian probability density. The radius of the filter was chosen as follows. A series of radii were selected (100, 200, 300, 400, 500 and 600 m) and the Boosted Regression Trees model for the year 2008 (see below) was run with each of these radii. The radius providing the best fit to the data was 100 m (Fig. 1) and thus was selected for further modelling.

Ips typographus infestation spots were surveyed by helicopter in both the study and validation areas in September 2007 and 2008, while in 2009 only the study area was surveyed. Current-year attacks were identified by the colour of killed trees' crowns. The location of each infestation spot was recorded by GPS and its size was classified in one of four classes: 5–10, 11–25, 26–50 or >50 killed trees. In November 2007 a sample of 163 randomly chosen infestation spots from the helicopter survey were validated from the ground. Each tree was checked for *I. typographus* galleries up to 3 m height by removing bark or by observing galleries higher up in places of woodpecker activity. Of 1620 checked spruces 1347 (83%) were confirmed to have been attacked by *I. typographus* in the same year. This figure is most probably an underestimate because *I. typographus* attacks above 3 m were only possible to verify if woodpeckers had removed the bark. The same infestation spots were checked again in the following summer to record the number of harvested spots. Of the 163 infestation spots, 52% were cut and most of them during the winter. In another study, conducted in the same region in 2007, 42% of the *I. typographus* new generation beetles from standing trees were estimated to hibernate in the ground (Komonen et al., 2011) where they are not affected by harvesting operations. In addition, most of the bark from *I. typographus*-killed

trees falls of during harvesting and hibernating adults in such bark may survive until next spring (Schroeder, unpublished). Maps of the forest predictors, bark beetle predictors and infestation spots are presented in the online version (Supplementary material, Figs. S1–S7).

2.4. Boosted regression trees modelling

To construct the database of the presence/absence of infestation spots, required to construct the Boosted Regression Trees (BRT) models, a large number of pseudo-negatives were created by randomly distributing points in the study area and excluding points falling in pixels where there was an infestation spot or "no data", i.e. pixels where there was no spruce. Spruce occurred in 78% and 80% of the pixels in the study and validation areas, respectively. In order to use training data with a balanced ratio of positives and pseudo-negatives, a Monte Carlo procedure was implemented to produce balanced sub-samples of positive and negative cases over 10 iterations. This means that the predicted probabilities of presence of infestation spots do not reflect absolute values of risk but relative values. Each sub-sample was randomly divided into a training set and a validation set. The training sets were used to build BRT models while the validation sets were used to evaluate the goodness of fit of the models. For the BRT model, we used 10 sets of training and test points for cross-validation, a tree complexity of 4, a learning rate of 0.005, and a bag fraction of 75%. Using those parameters, the cross-validation stepwise function presented by Elith et al. (2006) was used to identify the optimal number of model trees.

In contrast to most statistical methods, the BRT approach does not provide hypothesis tests to assess the significance of individual variables. However, the relative contribution of each predictor variable in a BRT model can be evaluated by estimating the proportion of times that a variable is selected for a splitting knot in a tree, weighted by the squared contribution of the tree to model improvement (Friedman and Meulman, 2003). This contribution was estimated for each of the 10 BRT models, and averaged to obtain an overall measure for each predictor variable. The profile of the fitted value and each predictive variable was also averaged over the 10 runs to determine the relationship between the predictor and predicted values.

2.5. Model evaluation

As indicators of goodness of fit, we estimated the area under the curve (AUC) of the receiver-operating characteristic plots (ROC-curves). Although the use of AUC as a single measure of goodness of fit in distribution modelling has recently been questioned (Lobo et al., 2008), it was used in this study because it was applied to similar geographic areas, with similar densities of negative points, thus allowing valid comparison of the performance of our models.
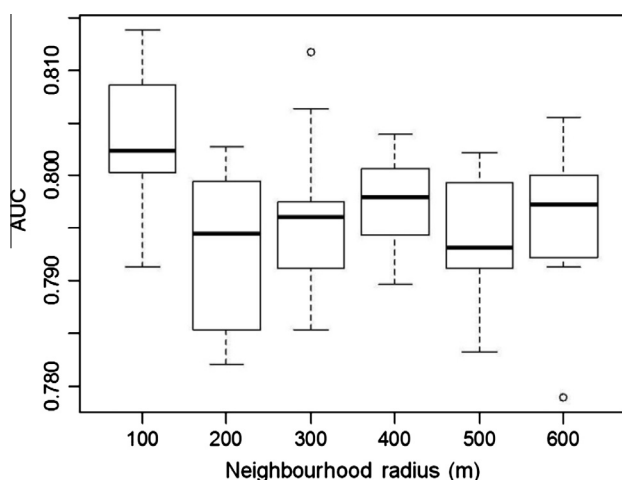

Fig. 1. Area Under Curve (AUC) of the autoregressive logistic regression model predictions for indicated neighbourhood radii. The contribution of each neighbouring cell was estimated using a Gaussian filter with the radius corresponding to the 95% percentiles of the distribution.

Separate models of infestation spots in 2007, 2008 and 2009 were trained. To evaluate whether adding the two bark beetle predictors would improve them, the models for 2008 and 2009 were tested with and without these predictors (but not the 2007 model, due to the lack of information on the bark beetle predictors for this year). Based on the mean AUC values from the ROC curves, three types of validations were applied: (i) the default validation, i.e. quantifying the AUC of each model using a different set of points from the set used to train the model; (ii) the 2008 models were validated against the 2009 data for the same area (i.e. extrapolating over time) and (iii) the 2008 models for the study area were validated against the 2008 data for the validation area (i.e. extrapolating over space).

All data were processed in ArcMap (ArcGIS 10, ESRI, Redland, CA, USA) and R version 2.14.2 (R Development Core Team, 2012).

3. Results

In total, 5000 *I. typographus* infestation spots were recorded in the study area during the three study years and 3208 in the validation area in 2007 and 2008 (Table 1). The smallest spot size class (5–10 trees) was dominant in both the study and validation area (Fig. 2). The spots were rather homogenously distributed across the landscape (see Figs. S5–S7).

The ROC curves for the default validations (i.e. validations of the predictions of infestation spots in the same area in the same year) of models including only forest predictors resulted in mean AUC values of 0.729–0.765 (Fig. 3). When the two bark beetle predictors were included the AUC value for the 2009 model increased from 0.765 to 0.818, but there was no change in the value for the 2008 model. When the 2008 models were applied to the same area, but the following year (2009), there was no reduction in the AUC values compared with those of the default 2009 models. Similarly, there was no reduction in AUC values when the 2008 model including bark beetle predictors was applied to the validation area (different area) in the same year, although application of the 2008
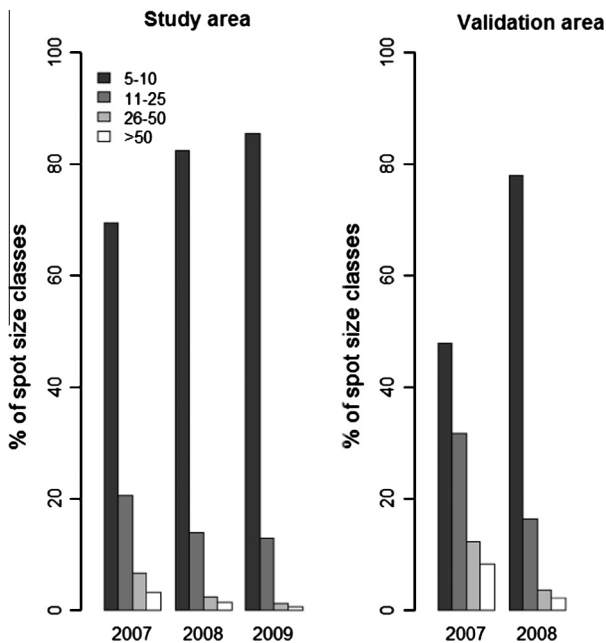

Fig. 2. Percentages of the four infestation spot size classes for each year in the study and validation areas. In 2009 no helicopter survey was conducted in the validation area. The figures in the legend represent the number of killed trees for each spot size class.
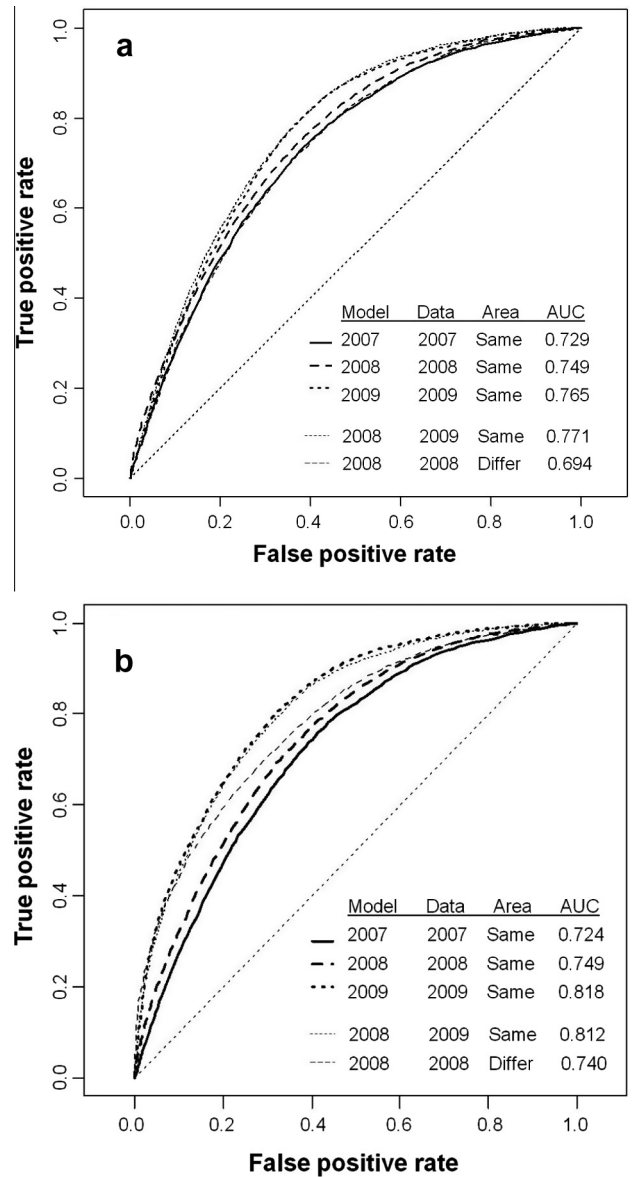

Fig. 3. ROC (receiver operator characteristic) curves and AUC (area under curve) values for models predicting risks of *I. typographus* infestation spots. (a) Models only including forest predictors. (b) Models including both forest and bark beetle predictors for 2008 and 2009 (no model including bark beetle predictors was constructed for 2007). 'Model' refers to the year in which data used to construct the model was collected, 'Data' refers to the year the model was validated against, 'Area' indicates whether the model was validated against the same area or a different area (i.e. validation area) and 'AUC' is the estimated accuracy of the models. The 'True positive rate' (*y*-axis) and 'False positive rate' (*x*-axis) refer to percentages of correct and incorrect prediction values, respectively.

model without bark beetle predictors resulted in a reduction in the AUC value from 0.749 to 0.694.

Spruce volume was the most important predictor in all models, with relative contributions (RC) of 68–72% in the models without bark beetle predictors (Fig. 4) and 43–61% in the models including bark beetle predictors (Fig. 5). In the models without bark beetle predictors, tree height was the second most important predictor (RC = 14–18%), followed by birch volume (RC = 10–11%) and distance to clear-cut (RC = 3–4%). The two bark beetle predictors contributed more in 2009 than in 2008. In 2009 they were the second (neighbouring infestation) and third (local infestation) most important predictors, with RC values of 20% and 15%, respectively (Fig. 5b). In 2008 they were the third and fifth most important predictors with RC values of 11% and 3%, respectively (Fig. 5a).
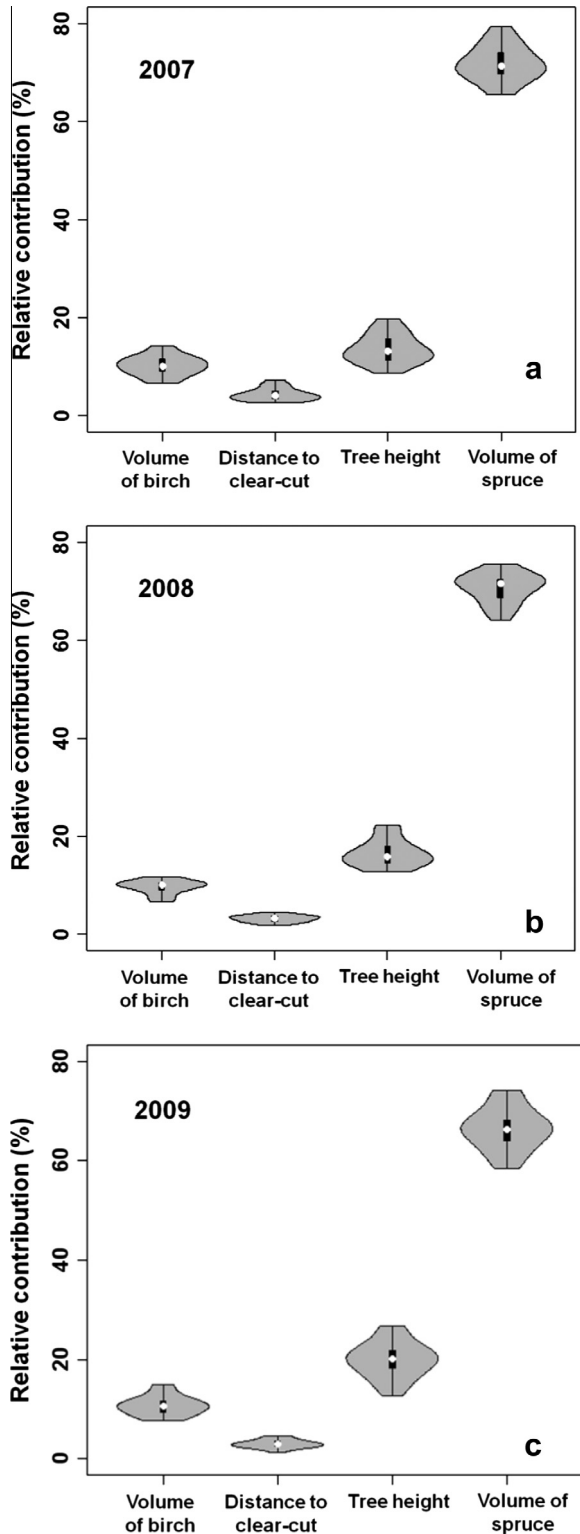
Fig. 4. Relative contributions of predictors in models predicting risks of *I. typographus* infestation spots based only on the forest predictors in (a) 2007, (b) 2008 and (c) 2009. The white central spots represent the median values and the black boxes represent the 25% and 75% quartiles. The grey shapes around the boxes illustrate the frequency distributions.

The BRT profiles of fitted values for individual predictors were similar between models with and without bark beetle predictors (Figs. 6 and S8). There was a positive association between birch volume and infestation risk up to a peak at approximately
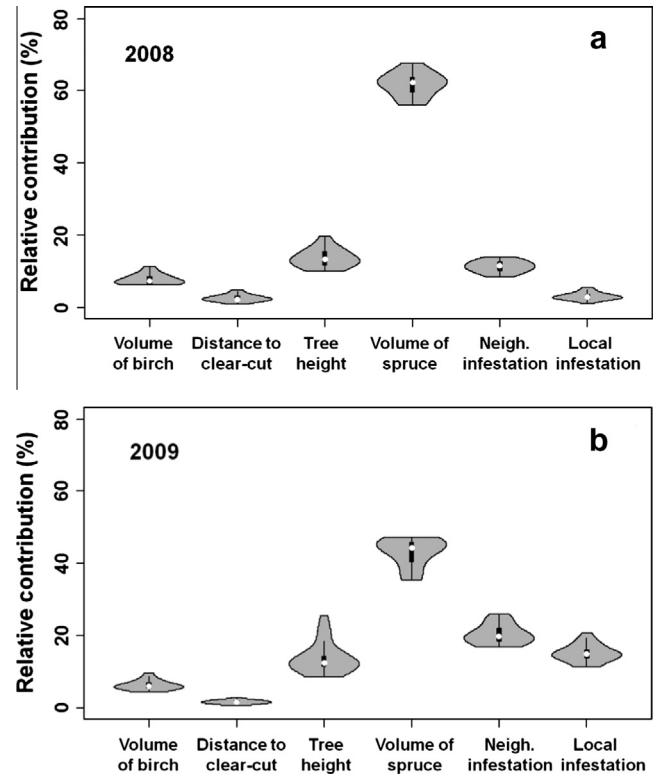

Fig. 5. Relative contributions of predictors in models predicting risks of *I. typographus* infestation spots based on both the forest and bark beetle predictors in (a) 2008 and (b) 2009. The white central spots represent the median value and the black boxes represent the 25% and 75% quartiles. The grey shapes around the box illustrate the frequency distributions.

25 m^3 ha^{-1}, after which the risk decreased (Fig. 6a). In 2007 and 2008 there was a weak negative relationship between infestation risk and distance to clear-cut (Fig. 6b). Tree height was associated with increased infestation risk above heights of 10 m in 2008 and 15 m in 2009 (Fig. 6c). The fitted functions for all models showed a strong positive effect between spruce volume and infestation risk up to about 200 m^3 ha^{-1}, where the relationship levelled out (Fig. 6d). Both bark beetle predictors showed a positive association with infestation risk (Fig. 6e and f).

The maps of predicted risks of *I. typographus* infestation spots in the study area generated by the different models were similar, indicating that high risk pixels were most frequent in the central-east and south-eastern parts of the landscape (Fig. 7).

4. Discussion

In all models, spruce volume was the single most important variable predicting where the risk for new infestation spots was highest. To our knowledge this is the first demonstration of a strong positive relationship between host tree volume per unit area at the stand scale (i.e. m^3 of growing stock of spruce per ha) and risk of bark beetle infestation. This result is in agreement with previous studies which have demonstrated a positive relationship between the risk of tree mortality caused by *I. typographus* and the proportion of spruce (Netherer and Nopp-Mayr, 2005; Overbeck and Schmidt, 2012). In addition, host tree basal area (Negrón and Popp, 2004; Negrón et al., 2008) and crown closure (Powell et al., 2000; Robertson et al., 2008) have been shown to be positively related to risks of infestation by *D. ponderosae*, and both of these variables are positively related to volume (Popescu et al., 2003; Gobakken and Næsset, 2004).
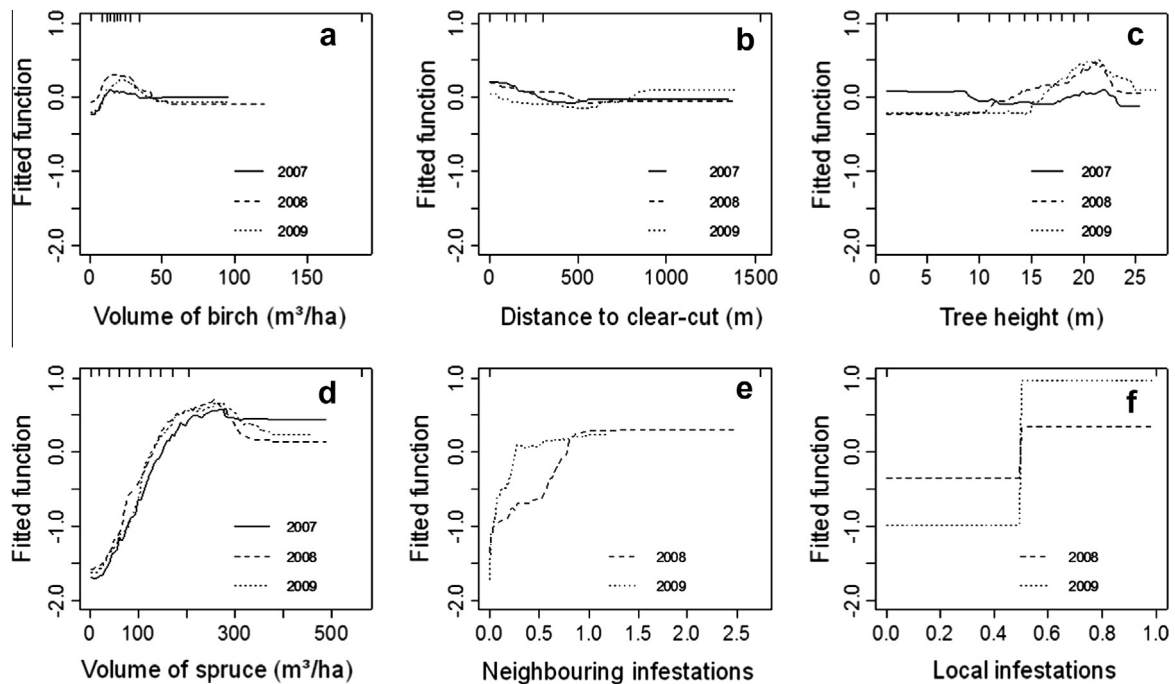
Fig. 6. BRT profiles of fitted values for the individual predictors. The profiles for 2007 are based on the model including only forest predictors while the profiles for 2008 and 2009 are based on models including both forest and bark beetle predictors. For models only including forest predictors for 2008 and 2009 see Fig. S8. The upper marks represent the distributions of the data.

The linear increase in risk with increasing values of spruce volume (m^3 ha^{-1}) demonstrated by the fitted values (Fig. 6d) may be a result of an increased probability of presence of trees susceptible to *I. typographus* colonization within a 100 × 100 m pixel. At volumes exceeding 200 m^3 ha^{-1}, representing pixels with high densities of older trees, such trees may always be present and thus the risk for formation of an infestation spot will not continue to increase (even though the volumes of killed trees may continue to increase).

The rather small contribution of the bark beetle predictors was unexpected since earlier studies have demonstrated that the risk for new *I. typographus* infestation spots is much higher close to infestations from the previous year (⩾96% of the infestation within 500 m) (Wichmann and Ravn, 2001; Kautz et al., 2011) and that the distance from previous attacks is relatively more important than stand characteristics for the risk of *I. typographus* infestations (Lausch et al., 2011). One explanation for the different result of the present study could be that most infestation spots were small (i.e. only 5–10 killed trees). Thus, the importance of such small local populations in relation to immigrating beetles should be less compared with a situation with larger local populations (i.e. infestation spots from the previous year). In the study by Lausch et al. (2011) conducted in the Bavarian Forest National Park in Germany, the infestation spots during outbreak periods were much larger than in the present study (Kautz et al., 2011). In addition, the forest in the national park was dominated by continuous old mature spruce forest while in our managed study landscape mature stands are fragmented (as a result of small stand sizes) and the landscape is dominated by young and middle-aged stands. This larger variety of stand types should increase the predictive power of forest variables.

The radius providing the best fit for the bark beetle predictor neighbouring infestations was the shortest distance tested (i.e. 100 m). Since most spots belonged to the smallest size classes, representing small local beetle sources, a larger radius could have been expected due to a greater importance of beetles immigrating from the large numbers of more distant spots in the adjacent landscape. A possible explanation for this seemingly contradictory

result is that the spots were rather homogenously distributed across the landscape, resulting in small spatial variation in densities of flying beetles, and thus a low predictive value of more distant beetle sources even though they contributed to spot formation.

Contrary to the hypothesis that the presence of birch in spruce stands reduces the risk of *I. typographus* infestations (Byers et al., 1998; Zhang et al., 1999; Zhang and Schlyter, 2004), our results indicate that the direction of the response may differ depending on the volume of birch. The fitted functions indicated a positive relationship between infestation risk and volume of birch up to 25 m^3 ha^{-1}. This pattern was consistent over the three year period and was not due to a positive correlation between birch volume (⩽25 m^3 ha^{-1}) and spruce volume in the study area ($R^2 = 0.002$). Neither was there any correlation between birch volume and total volume ($R^2 = -0.13$) which could have implied an effect of increased tree competition reducing the vigour of the spruce trees (Hayes et al., 2009). Instead, we hypothesize that this pattern is caused by a "push–pull" effect (Cook et al., 2007), arising from the attraction to aggregation pheromones ("pull") being stronger if repellents (non-host volatiles from birch) simultaneously "push" the beetles towards the attracting pheromones (Lindgren and Borden, 1993; Cairns et al., 2008). The decline in infestation risk for birch volumes >25 m^3 ha^{-1} may be due to the repellents that exceeding the strengthening of the "pull" effect.

Tree height and distance to clear-cut both contributed little to the models. The explanation for a low contribution from tree height could be that this variable included heights of not only the host spruce but also of all other tree species. The fitted functions for 2008 and 2009 indicated a threshold at a tree height of 10–15 m, above which there was a positive relationship between height and infestation risk. This is consistent with smaller trees having bark that is too thin to be suitable for *I. typographus* (Grünwald, 1986). The low contribution of distance to clear-cut could be a result of most of the edges being created by the storm Gudrun in January 2005 which means that they were already three to five years old during our study period. In accordance with this
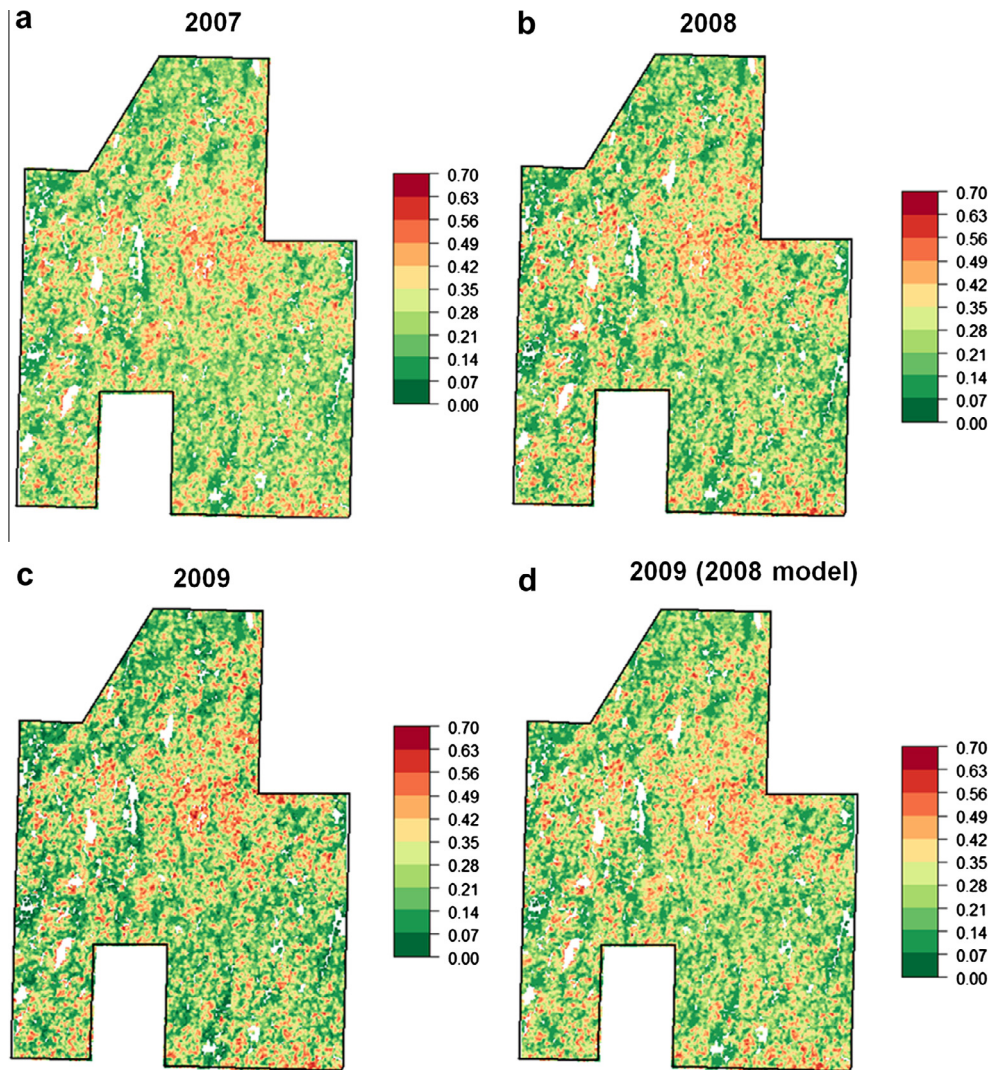
Fig. 7. Maps of the study area showing the relative predicted risk of having at least one *I. typographus* infestation spot at 100 × 100 m resolution. The predictions are based on (a) the model of 2007, (b) the model of 2008, (c) the model of 2009, and (d), the model of 2008 which were used to predict risks for 2009. The 2007 model only included forest predictors while the 2008 and 2009 models also included bark beetle predictors.

hypothesis, the fitted functions for 2007 and 2008 showed a trend of increased infestation probability at the shortest distances while this was not the case in 2009.

Our results demonstrate that the BRT modelling approach can be successfully used to create operational risk-rating maps for bark beetle-caused tree mortality across large forest areas based on GIS-layers reflecting forest susceptibility and beetle pressure. In a comprehensive assessment of presence/absence distribution modelling methods, Elith et al. (2006) found that BRT performs best, along with the maximum entropy method. BRT combines the strengths of regression trees (which model responses by recursive binary splits of the predictors) and boosting (which iteratively combines many models to increase predictive performance). A particularly valuable feature of BRT modelling is its capacity to plot the effect of each variable on the predicted output value (fitted value). BRT reportedly generates better predictions than linear regression approaches (Elith et al., 2006), implicitly accounts for interactions among predictor variables, and allows for non-monotonous relationships between the modelled response and the predictor variables (Elith et al., 2008). BRT modelling has been previously used in ecological studies to predict species distributions (Leathwick et al., 2006; Sinka et al., 2010) and disease risks (Martin et al.,

2011; Van Boeckel et al., 2012), but this is the first study to use it for predicting risks of bark beetle-caused tree mortality.

The applicability of our approach, and results, for *I. typographus* outbreaks in other areas depends on several factors. The approach should be feasible also in areas where other predictors are important than the ones included in the present study (e.g. in mountainous areas) as long as these predictors are available at a sufficiently high resolution and quality across landscapes. However, the importance of different predictors may vary between regions as a result of e.g. differences in forest composition. In large areas with unmanaged continuous old spruce forest beetle pressure may be more important than forest predictors as a result of large local beetle populations and small variation in forest suitability.

5. Conclusion

Our study demonstrates that it is possible to map risks of bark beetles causing tree mortality across large forest areas by using easily accessible satellite data describing forest characteristics and aerial surveys of infestation spots in the previous year. This is encouraging since the accuracy and interpretation of satellite

data are rapidly improving. Thus, in the future, providing forest owners with detailed risk-rating maps during outbreaks might be a routine procedure, which could improve assessments and control measures by allowing them to focus on identified high-risk stands. For *I. typographus* outbreaks in managed forest landscapes our results also indicate that including information about beetle pressure does not improve the models much. This study is at the forefront of applying BRT modelling to predict infestation and creating risk-rating maps for bark beetle infestations. We strongly encourage future studies of forest pests to use this method.

In addition, our study is the first to document the spatial distribution and frequency of sizes of *I. typographus* infestation spots in large managed forest landscapes during an outbreak. The frequencies were strongly skewed towards the smallest classes and they were spread out across the landscape. Thus, it is a real challenge for the foresters to find and conduct sanitation cuttings of killed trees before the new generation of beetles emerges in summer. In such a situation detailed risk-rating maps would be of great value for the foresters.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.01.025.

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