

Adaptive roadside sampling for bark beetle damage assessment

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Abstract

Bark beetle infestations are often scattered throughout the forest landscape and therefore difficult to accurately and rapidly assess. We tested a roadside sampling technique in a pure maritime pine forest (*Pinus pinaster*) of ca. 1300 ha where bark beetle outbreak foci were observed following a windstorm. The sampling method relied on the count along stand edges of all dying or dead trees sighted within a fixed distance from the road. About 2300 trees attacked by *Ips sexdentatus* were recorded and located using colour-infrared aerial photography. Accuracy of the infestation map was verified by ground sampling. Piles of cut logs stored along the edge significantly increased the percentage of attacked trees in the neighbouring stand. However, the percentage of attacked trees within the stand edges did not differ with the percentage within the stand interior. It allowed us to use stand edges as sampling units to estimate the mean percentage of attacked trees per stand. At the stand scale, the use of a fixed 10 m wide strip along stand edges maximized the detection of attacked trees and minimized the bias of estimated percent of attacked trees. Based on GIS data, various stratified roadside sampling plans with increasing numbers of edges per stand and increasing numbers of stands per forest were simulated by bootstrap resampling. In a forest without any storage of cut logs, systematic roadside surveys underestimated the level of damage. The sampling accuracy increased with the kilometers of edges surveyed. In a forest with piles of cut logs on which bark beetles can breed, the best option was an adaptive sampling plan where at least two additional consecutive edges were observed in stands close to the pile. As compared to systematic sampling plans, adaptive plans were three times less expensive in terms of sampling effort for the same accuracy. Overall, adaptive sampling plans were also more robust as they provided less biased estimates as the proportion of stands with nearby piles increased in simulated forests.

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1. Introduction

Climatic events such as storms, lightning strikes or droughts are known to favour the spread of some forest pest insects like bark beetles (Coulson et al., 1999; Wichmann and Peter Ravn, 2001; Eriksson et al., 2005; Gilbert et al., 2005) whose spatial distribution and associated economic consequences are scale-dependent. As a consequence, forest damage assessment and monitoring often entail a multi-scale approach (Powers et al., 1999). Forest managers require forest health information

ranging from the regional scale (for sustainable management planning purposes) to stand scale (detailed local information). The landscape scale (1:10,000–1:50,000) has often been considered the most relevant spatial scale for insect pest monitoring as well as for direct control and salvage operations (Wulder et al., 2004; Wainhouse, 2005; Fettig et al., 2007). Forest pest monitoring at the landscape scale requires considerable sampling effort as it is intended to provide both accurate and spatially explicit information over large areas. The situation is even more problematic when pest density is low and when attacked trees are scattered within the forest landscape.

Wulder et al. (2006) reviewed the solutions offered by aerial overview surveys based on remotely sensed data. Moderate resolution data such as those provided by Landsat TM may be appropriate to detect large infestation levels but do not allow a proper quantification in case of low pest density and/or random

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spatial distribution of damages. On the other hand, the accuracy of individual attacked tree mapping may be improved by the use of multi-date imagery or a high spatial resolution (Bone et al., 2005), but these methods require sophisticated technology and turn out to be quite expensive when applied over large areas. Widely used for wildlife inventories, the strip sampling method allows a rapid survey of large areas. Commonly implemented along randomly spaced lines in aerial or boat surveys, it is often considered as wasteful for the estimation of sparse and/or clustered populations (Buckland et al., 1993; Schwarz and Seber, 1999; Pollock et al., 2002). Adaptive sampling in which sampling effort is increased around infection spots has proven to provide a better estimate of damage level than simple random or systematic sampling schemes (Thompson, 2002). It can be combined with conventional methods such as line transect sampling (Pollard et al., 2002) or cluster sampling (Turk and Borkowski, 2005). However, inventories remain time consuming or poorly applicable in the field when large areas are to be urgently surveyed. To circumvent this limitation, the variable area transects (VAT) sampling appears to be an interesting alternative (Engeman and Sugihara, 1998). This method consists of fixing the width of a narrow strip transect of observation and to adapt its length to the occurrence of damage. It seems to offer a good compromise between the accuracy of the estimates and investment in field work. It has been successfully tested on different crop damages of various densities but only at the stand scale (Engeman et al., 2005).

This study explored various spatially explicit sampling plans in order to develop a practical and cost-effective method to assess the density of trees attacked by bark beetles within a fragmented landscape. Because forest plantations display a dense network of roads due to timber activities and fire protection requirements, we developed a sampling strategy that takes advantage of this feature over large areas. We used the strip transect approach in which only damaged trees sighted from the road within a fixed width and continuous strip along stand edges had to be recorded. It can be considered as a combination of distance and quadrat methods. Accuracy of estimations will thus vary according to the total length of edges and the width of the strip observed. Assumptions were that the monitoring staff ignored both the spatial distribution of attacked trees and the location of piles of cut logs.

The survey was undertaken within monospecific plantation forests of maritime pine (*Pinus pinaster* Ait) covering 1 million ha in southwestern France. In that region the pine stenographer beetle (*Ips sexdentatus* Boern.) can occur as a severe pest showing complex spatial patterns with various degrees of patchiness (Bouhot et al., 1988; Gilbert et al., 2005). Our approach was to test such a roadside-based sampling in a 1300 ha forest in which all attacked trees were spatially located by means of colour-infrared aerial photography. With the exact set of attacked trees, we investigated first whether local factors might affect the spatial distribution of damage in order to design a stratified sampling plan. Then, using bootstrap resampling, we explore the performance of several sampling schemes to minimize both the number of edges per stand and the number of stands to be sampled.

2. Methods

2.1. Study site and data collection

2.1.1. History of storm damage

The study was conducted in the state forest of Lagnereau located in the southwestern France (44°30'N, 1°14'O, Fig. 1). This forest covers 1300 ha of pure maritime pine plantations, with a mean annual temperature >12 °C, an average annual rainfall of 700 mm and a low elevation (<50 m). It is divided into 73 stands of 16 ha on average and tree age ranging from 4 to 55 years. These features are representative of the typical rotation cycle in this region (ca. 40–50 years). All stand edges were bordered by forest tracks (125 km in total in the studied forest) and could be observed from a car. In December, 1999, the southwestern France was struck by a devastating hurricane which felled more than 27 million m³ of timber. Sanitation removals of fallen trees were completed between November 2000 and the end of 2001 at the study site. Pine logs were temporally stored in piles along stand edges during the process of fallen tree removal. Likely, the pine stenographer beetle was able to use this breeding material to build up its populations and mass-attacks of standing trees were observed during autumn in 2001.

2.1.2. Spatial database

We carried out a complete inventory of damaged trees in all stands of the study site. The symptoms of trees currently infested by bark beetles are pitch tubes on the bole and at least a part of the crown faded to yellow-red which is mostly visible during the autumn season at those latitudes (Lieutier et al., 2004). An aerial survey was undertaken in September 2001 and the entire forest was covered by 70 colour infrared photographs

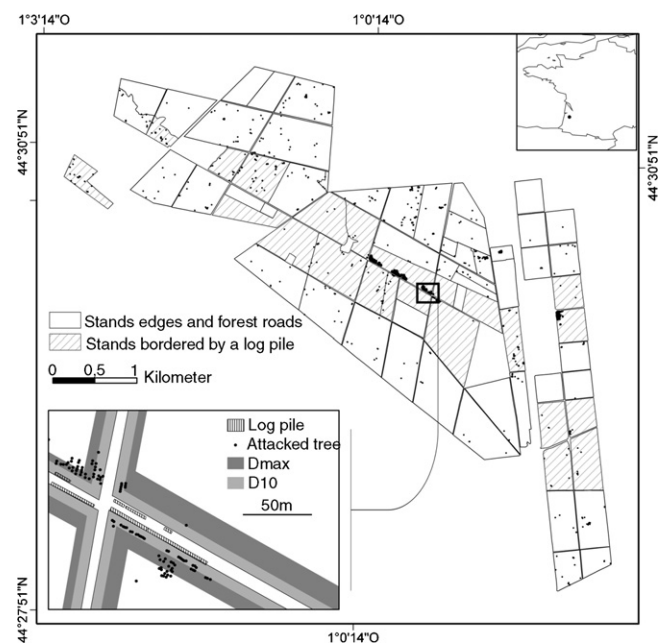


Fig. 1. Study site location and map of trees attacked by *I. sexdentatus* in 2001. The zoom window shows the piles of pine logs stored at stand edges and the black points represent the attacked trees. Grey strips illustrate the sighting distances from the road of a D_{10} and D_{max} width within the stands.

(Kodak 2443, scale = 1:5000, focal length = 210 mm) of high spatial resolution (about 15 cm). In addition, we conducted an exhaustive ground sampling to establish the cause of decay or mortality of all damaged trees in the central part of the forest ($n = 19$ stands). These data were used to calibrate the photo-interpretation phase. Spatial information was summarized using ArcInfo software (Workstation 8.1, ESRI, Redland, CA, USA). In order to estimate tree densities in the stands, a systematic grid (100 m \times 100 m) of square windows (0.1 ha) was developed using aerial photographs. Information about every stand edge in the forest, the position of log piles and the exact location of all trees attacked by *I. sexdentatus* were stored in a geodatabase (Fig. 1).

2.1.3. Field survey procedures

A drive-through survey was also carried out in September 2001, in which observers travelled along forest roads with a maximum speed of 15 km/h. The maximum sighting distance of attacked trees (from the road) was estimated for each stand edge ($n = 304$) and thereafter referred to as D_{\max} . The shortest D_{\max} recorded was 10 m, a value roughly corresponding to the observation of the first two rows of trees in maritime pine plantations. We further used in our sampling schemes these two sighting distances within which 100% of attacked trees by the pine stenographer could be sighted from the forest road: a fixed one up to 10 m (D_{10}) within the stand and the other one, from the road up to D_{\max} (D_{\max}), specific for each stand edge (Fig. 1). Because the study site showed no topographic variation, we assumed that the maximum sighting distance (D_{\max}) was only affected by stand characteristics such as stand age, tree density and the orientation of plantation lines relative to the road axis.

2.2. Multi-scale analysis

Prior to developing sampling plans based on stand edges observations, the spatial distribution of attacked trees was analysed within each stand. Percentage of attacked trees within all stand edges (Se = a strip of D_{10} or D_{\max} wide along all stand borders) was compared to percentage of attacked trees in the whole stand (S) or within the interior of the stand ($Si = S - Se$) with paired Wilcoxon tests. We made the same comparison for stands bordered or not with log piles.

2.2.1. Stratification

Various ecological factors are likely to affect the spatial distribution of *I. sexdentatus* and, therefore, could be used to stratify sampling (Southwood and Henderson, 2000). In cultivated and even-aged forests, tree density is well correlated with tree age, diameter and height. In the studied forest, tree density values, at the stand level, were distributed among three classes (<200, 200–1000, >1000 trees/ha). Piles of pine logs often function as sources of bark beetles able to mass attack nearby standing trees. Such piles were stored near 23 of the 73 studied stands. We tested the effect of both tree density and presence (distance to a pile less than 20 m of one of the edges) or absence of log piles on the percentage of attacked trees in the

whole stand. Because of the probable spatial dependence of attacks between stands and the lack of balance between factor classes, a two-factor randomization test of variance was used. A distribution of the pseudo F -statistic (F_p) under the null hypothesis was created using 1000 randomizations (Manly, 1997). The F_p distribution was obtained by permuting labels on the multivariate observations that identify them as belonging to a particular class. A P -value was computed as the proportion of the F_p values superior to the observed F -value.

2.2.2. Roadside estimator

Attacked trees that could have been sighted from the road within fixed values of distance (D_{10} and D_{\max}) were selected *a posteriori* by geoprocessing using buffer along stand edges. If L is the length of a stand edge and D the sighting distance (D_{10} and D_{\max}), the area of the narrow strip observable from the road is $L \times D$. The estimation of the number of attacked trees within the strip (N_{strip}) was scaled up to the stand of area A using Eq. (1):

$$N_{\text{stand}} = \left(\frac{A}{LD} \right) N_{\text{strip}} \quad (1)$$

Assuming the tree density (d) to be homogeneous within each stand, the percentage of attacked trees per stand ($\% N_{\text{stand}}$) given by Eq. (2) was used to compare infestation levels in stands of various tree densities:

$$\% N_{\text{stand}} = \frac{N_{\text{stand}}}{dA} \times 100 \quad (2)$$

It must be noted that tree density in the stand was the only information needed prior to survey and could also be estimated from the road. The estimation of the percentage of attacked trees at the forest level was obtained by averaging the estimation in the sampled stands. Forest landscape was thus considered as a set of stands and spatial relationships between stands were not taken into account.

2.2.3. Stratified sampling simulations

We focused on the effect of sampling effort on accuracy of estimation of the percentage of attacked trees. We simulated various sampling plans by resampling with replacement. Bootstrapping is a resampling technique that uses the observed samples to randomly generate samples of desired size (Efron and Tibshirani, 1998).

At the stand scale, estimation of the percentage of attacked trees was assessed using an increasing number of edges per stand. For each stand, the starting edge was randomly selected and then consecutive borders were added. We simulated samplings in 24 contrasted situations: 3 types of stands (stands with log piles, stands without log piles and all stands) \times 4 sample sizes (1, 2, 3 and All edges per stand) \times 2 sighting distances (D_{10} or D_{\max}).

At the forest scale, we estimated the mean % of attacked trees with increasing numbers of sampled stands.

We considered two sets of stands: one comprising all the stands ($n = 73$ stands) and a subset only comprising stands

without log piles ($n = 50$ stands). We first investigated two systematic sampling plans which consisted in the observation of either 1 or All borders per stand. As no reliable data about the location of log piles is available, we assumed that this information cannot be used to determine sampling plans. However, given the aggregative behaviour of bark beetles, we also chose to test several adaptive schemes to concentrate the sampling effort around log piles. The adaptive sampling method relies on increasing the number of consecutive edges observed in a stand if the first randomly sampled edge was in the direct vicinity of a log pile. This led us to test three adaptive roadside surveys by adding one (“1 or 2”), two (“1 or 3”) or all remaining edges (“1 or All”) of the stand in the sample.

At each scale, a single simulation was defined as the combination of a sample size (border or stand), a transect width (D_{10} or D_{\max}) and a type of stand (with or without log piles). The criterion for comparing estimates was the mean bias, i.e. the mean difference, in a sample of n stands, between the estimated and the observed % of attacked trees per stand (% N_{stand}) in the aerial photos (Eq. (3)):

$$\text{mean bias} = \frac{\sum(\text{estimated \% } N_{\text{stand}} - \text{observed \% } N_{\text{stand}})}{n} \quad (3)$$

It enables comparing several stands of different tree density. Each run was performed 5000 times using the R software (R Development Core Team, 2006) and the mean value of the mean bias, referred to as bootstrap bias (BB) was computed according to Eq. (4):

$$\text{bootstrap bias} = \text{BB} = \frac{\sum(\text{mean bias})}{5000} \quad (4)$$

Similarly, the mean% of attacked trees per stand (MPAT) and the related bootstrapped mean (BM)% of attacked trees were calculated according to Eq. (5) and (6), respectively:

$$\begin{aligned} \text{mean percentage of attacked trees} &= \text{MPAT} \\ &= \frac{\sum(\text{estimated \% } N_{\text{stand}})}{n} \end{aligned} \quad (5)$$

$$\text{bootstrap mean} = \text{BM} = \frac{\sum(\text{MPAT})}{5000} \quad (6)$$

2.2.4. Roadside sampling accuracy

Estimation accuracy was approached by the 95% bootstrap percentile confidence interval (CI 95%) of the MPAT distribution (Fig. 2). In order to compare different sampling strategies we computed a criterion of loss of accuracy (Δ) which represents the absolute % of attacked trees overlooked in the forest that one could allow. Three fixed values of Δ were investigated: 0.1, 0.05 and 0.01% of attacked trees. For each sampling plan, we added those percentages to the CI_{\max} , the confidence interval of the mean % of attacked trees obtained with the largest sample size (maximum number of stands in the simulated forest), providing a new and larger, i.e. more tolerant confidence interval, $\text{CI}_{\max} \pm \Delta$. Then, we looked for the

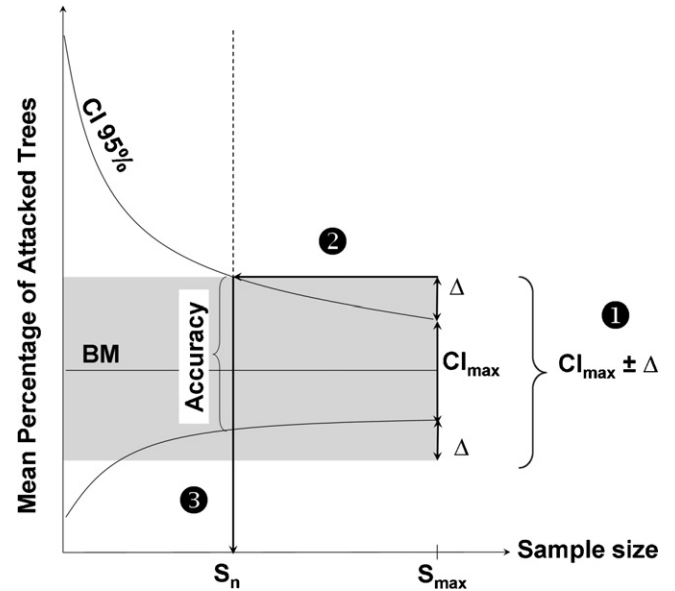


Fig. 2. Theoretical relationship between MPAT, the mean percentage of attacked trees ($\pm \text{CI } 95\%$) and the sample size (i.e. number of sampled stands). Bootstrap mean (BM) is computed over 5000 randomizations for each sample size. Δ is a fixed loss of accuracy which represents the % of attacked trees overlooked and CI_{\max} is the CI 95% obtained with the largest sample size simulated (S_{\max}). The diagram shows the steps of the process to determine the smallest number of stands (S_n) to sample in order to provide MPAT estimates, 95% of which are comprised within $\text{CI}_{\max} \pm \Delta$. In the first step, Δ is added to the upper and lower bound of CI_{\max} . Grey area illustrates the fixed limits of acceptable accuracy ($\text{CI}_{\max} \pm \Delta$). In the second step, we looked for the number of stands from which $\text{CI}_{\max} \pm \Delta$ starts completely overlapping CI 95%. In the third step, we inferred the corresponding sample size (S_n) and the corresponding accuracy.

smallest number of stands (S_n) to be sampled in order to provide 95% of BM estimates comprised within this new interval of confidence, or in other words, the number of stands from which $\text{CI}_{\max} \pm \Delta$ starts completely overlapping CI 95% (Fig. 2). Then we calculated the total strips length to be observed during the road survey of these S_n stands. This distance of observation was further standardized to a 1000 ha forest and the corresponding duration of observation was computed for a 15 km/h speed.

2.2.5. Roadside sampling robustness

We explored the performance of the present roadside sampling procedure across various simulated forests. Assuming the independency of attacks between stands, we simulated several mosaics of stands with unbalanced resampling. Various forests of the same size ($n = 73$ stands) were randomly simulated with an increasing proportion of stands with log piles (from 0 to 100%). It allowed the indirect simulation of forests with increasing numbers of attacked trees. For each proportion of stands with log piles, the bootstrap bias was computed by 5000 simulations with replacement. Then, for each simulated forest, we applied the same sampling plans as indicated above (two systematic and three adaptive). The same number of kilometers to be sampled was previously fixed in each sampling plan using a tolerated loss of accuracy of $\Delta = 0.05\%$.

3. Results

3.1. Local factors driving the spatial distribution of attacked trees

The percentage of attacked trees per stand based on aerial photograph interpretation was highly correlated with the percentage of attacked trees by *I. sexdentatus* recorded during the exhaustive ground inventory in the same stands ($n = 19$, $R^2 = 0.82$, $P < 0.001$). In the subsequent analyses, the remote-sensed data were therefore used as a reference allowing the inclusion of a greater number of stands. Fig. 1 shows the spatial distribution of the attacked trees throughout the study zone. It can be seen that the density of attacked trees was noticeably variable between stands and corresponded to spatial patterns ranging from randomness to very high clustering. Overall, the proportion of attacked trees was low 0.35% (2387 attacked trees), and ranged from 0 to 4.53% per stand. The percentage of attacked trees within the strip surrounding the stand was not significantly different from the percentage either in the stand interior or within the whole stand (Table 1). It allowed us to base a sampling strategy on the observation of stand edges. The randomization test of variance (Table 2) showed that the percentage of attacked trees within the whole stand was significantly higher in the presence of log piles near the stands (0.59% S.E. \pm 1.00 and 0.24% S.E. \pm 0.38, respectively, for stands with and without nearby log piles). Therefore, the presence of log piles was further used as a stratifying factor in roadside sampling simulations.

3.2. Effect of the number of sampled edges on damage estimation at the stand level

Field data showed the maximum sighting distance of damaged trees (i.e. D_{\max}) to be 39.8 m on average ($n = 304$, S.E. \pm 1.13). Resampling with replacement of an increasing number of edges per stand, according to D_{10} and D_{\max} provided an overview of the effect of both the width and the length of strip to be sampled on the estimate of % attacked trees at the stand scale (Fig. 3). It must be noted that for the maximum sample sizes only one combination was possible per stand (i.e. all stand edges observed) and consequently only the mean was computed and

Table 2

Randomization test of variance (ANOVA type III) of the effect of tree density (three levels) and presence of log piles nearby one stand edge, on the percentage of attacked trees per stand in 2001 (* $p < 0.05$)

| | Sum Sq | d.f. | F-value | $P(F_p \geq F)$ |
|------------------------|--------|------|---------|-----------------|
| Log piles | 2.067 | 1 | 4.82 | 0.033* |
| Tree density | 0.239 | 2 | 0.27 | 0.761 |
| Piles \times density | 1.032 | 2 | 1.20 | 0.290 |

F is the original F -statistic and F_p is the simulated value over 1000 randomizations created by permuting the observations.

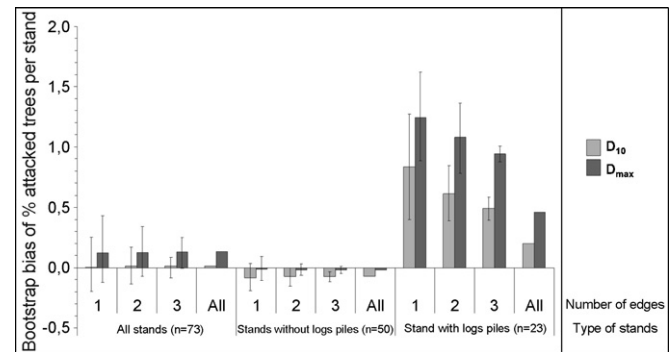


Fig. 3. Bootstrap bias (BB \pm CI 95%) of the percentage of trees attacked by *I. sexdentatus* per stand calculated from 5000 randomizations with replacement. Estimations were computed for an increasing number of consecutive edges per stand, using two distinct sighting distances (D_{10} and D_{\max}). Bootstrap bias was calculated in three samples of pine stands: in the 73 stands of the studied forest, in a subset of 50 without log pile nearby, in a subset of 23 stands bordered by a log pile. For subsets including all the stands or stands with no log piles, the starting edge was chosen at random. For the subset of stands with log piles, the starting edge was the edge bordered by a log pile. Then 1 means one edge with a nearby log pile, 2, 3 and All means one edge with a nearby log pile followed by 1, 2 or All the other edges with no nearby log piles.

no standard error could be shown. The percentage of attacked trees was clearly overestimated by the strip sampling in stands close to log piles (Fig. 3). In this case, both the bootstrapped bias and its confidence interval dramatically increased with the width of the strip (D_{\max}) and as the number of sampled edges decreased. The largest overestimation occurred when only the stand edge in front of the log pile was observed. For the stands with no nearby log piles, the bootstrap bias of % attacked trees estimate

Table 1

Total number (n) and mean percentage (\pm standard error) of trees attacked by *I. sexdentatus* in different parts of the 73 stands of the study site, in the 50 stands without a log pile stored on one of its edge and in the 23 stands with a log pile, respectively

| | | Edges | | Interior | | P (Wilcoxon) | Whole Stand | | P (Wilcoxon) |
|---------------------------------------|------------|-------|-------------------|----------|-------------------|----------------|-------------|-------------------|----------------|
| | | n | Mean % \pm S.E. | n | Mean % \pm S.E. | | n | Mean % \pm S.E. | |
| All stands ($n = 73$) | D_{10} | 327 | 0.36 \pm 0.09 | 2060 | 0.35 \pm 0.08 | 0.75 | 2387 | 0.35 \pm 0.08 | 0.73 |
| | D_{\max} | 1384 | 0.48 \pm 0.15 | 1003 | 0.32 \pm 0.11 | 0.11 | 2387 | 0.35 \pm 0.08 | 0.08 |
| Stands without log piles ($n = 50$) | D_{10} | 38 | 0.17 \pm 0.04 | 468 | 0.25 \pm 0.06 | 0.23 | 506 | 0.24 \pm 0.05 | 0.21 |
| | D_{\max} | 247 | 0.22 \pm 0.05 | 259 | 0.25 \pm 0.09 | 0.54 | 506 | 0.24 \pm 0.05 | 0.59 |
| Stands with log piles ($n = 23$) | D_{10} | 289 | 0.78 \pm 0.26 | 1592 | 0.57 \pm 0.22 | 0.27 | 1881 | 0.59 \pm 0.21 | 0.27 |
| | D_{\max} | 1137 | 1.05 \pm 0.44 | 744 | 0.46 \pm 0.22 | 0.10 | 1881 | 0.59 \pm 0.21 | 0.06 |

Edge represents a strip area of width equal to D_{10} or D_{\max} and length equal to the stand perimeter. The interior is defined as the complementary area between the whole stand and its edge (edge + interior = whole stand). P -values are the results of Wilcoxon paired tests comparing the percentage of attacked trees within the edge with the percentage of attacked trees in the interior or with the percentage of attacked trees in the whole stand.

remained virtually constant and very low (-0.07%) across sample sizes. The 10 m distance of observation consistently minimized the mean bias in stands close to a log pile and slightly increased the bootstrap bias in stands with no log pile. As it is clearly more practical in the field, only this constant sighting distance was used in further analyses.

3.3. Effect of the number of sampled stands on damage estimation at the forest level

At the forest scale, bootstrapping curves reported in Fig. 4 showed the same profile among sampling schemes. The bootstrap bias ranged from -0.09% to 0.01% (Table 3). It remained almost constant with increasing number of stands taken at random, due to the large number of randomizations (Fig. 4). The confidence interval (CI 95%) decreased sharply with increasing sampling effort from 1 to about 10 stands observed, then more smoothly from 10 to 50 or 73 stands (Fig. 4). However, sampling plans greatly differed in their absolute accuracy and in the minimum number of stands to be sampled to reach the fixed tolerated loss of accuracy (S_n , see Section 2) (Fig. 4, Table 3). To ease the interpretation of Table 3, we will only consider the intermediate value of accuracy loss (Δ), i.e. 0.05% of overlooked damaged trees.

Systematic sampling plans provided negative bootstrap bias estimates (-0.09% to -0.07% of attacked trees) in

forests without log piles but positive and almost null bias (0.01% of attacked trees) in forest with log piles. There was almost no effect of the number of edges sampled per stand on the level of bias. The sampling accuracy showed the opposite pattern. For a given value of Δ (i.e. $\Delta = 0.05\%$), the accuracy was always better when all edges per stand were assessed (Table 3) but this resulted in multiplying by four the sampling effort (in a forest with log piles, 18 and 72 km/1000 ha, respectively, for 1 and All edges sampled would have to be covered).

Adaptive sampling plans were only simulated for the whole forest with log piles (Table 3, Fig. 4) as they would have provided the same results as the systematic sampling plans (1 edge/stand) in forest with no log piles. The bootstrap bias showed a low underestimation of the mean percentage of attacked trees in the whole forest, ranging from -0.07% (for “1 or 3” and “1 or All” edges sampled) to -0.03% (for “1 or 2” edges sampled). Again, the accuracy showed the opposite pattern with a better accuracy obtained as the number of additional edges sampled per stand increased. The sampling effort did not vary between the three types of adaptive samplings (ca. 22 km/1000 ha for a $\Delta = 0.05\%$). However, for a given value of accuracy loss, a smaller number of stands (S_n) was needed in the adaptive “1 or All” scheme than in the “1 or 2” one (Table 3).

When comparing systematic and adaptive sampling plans in forests with log piles, it appears that adaptive plans lead to a

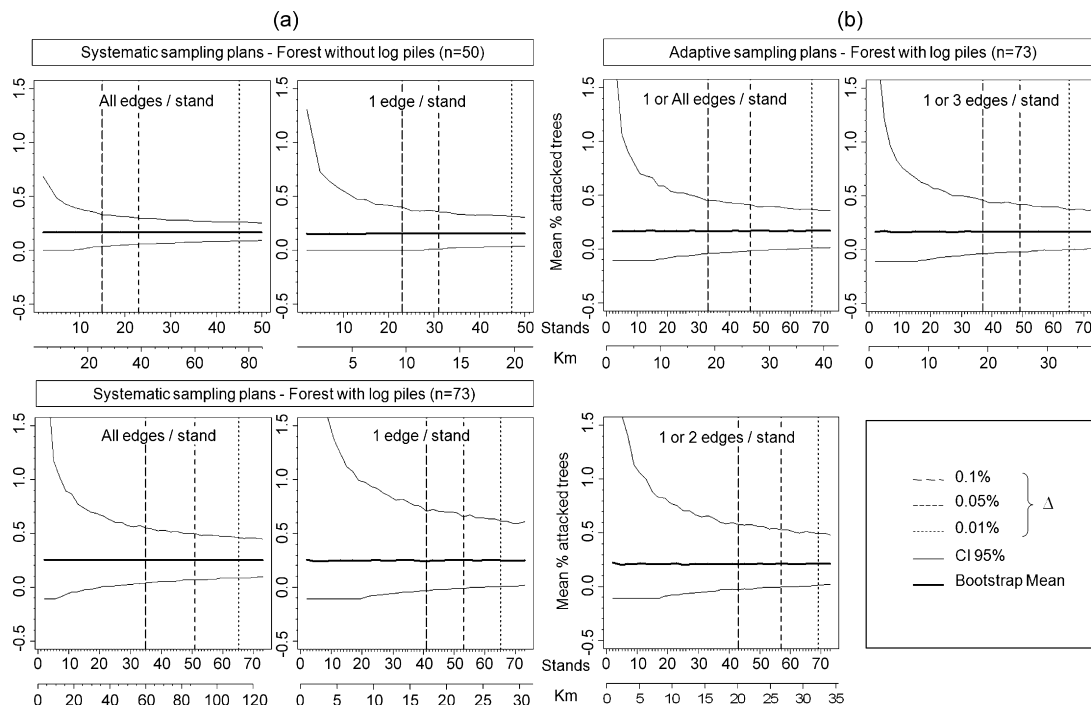


Fig. 4. Bootstrapped mean percentage of attacked trees (MPAT \pm CI 95%) by the pine stenographer beetle in a forest with or without the presence of log piles stored at stand edges. Bootstrap mean (BM) was computed over 5000 randomizations with replacement of an increasing number of stands surveyed and the equivalent distance observed (as kilometers along edges). Different sampling plans were simulated according to the number of edges per stand observed with a fixed sighting distance of 10 m into the stand edge (D_{10}). In systematic sampling plans (a), the number of edges per stand to be sampled was constant (1 or All). In adaptive sampling plans (b), a greater number of consecutive edges per stand (2, 3 or All) was sampled if the starting border was in the neighbourhood of a log pile. Vertical dotted lines show S_n , the minimum number of stands from which CI 95% $\pm \Delta$ starts completely overlapping CI 95% (see Section 2, Fig. 2) given three fixed losses of accuracy Δ (from left to right, $\Delta = 0.1, 0.05$ and 0.01% of attacked trees).

Table 3

Roadside survey simulations with a sighting distance fixed to 10 m from the road throughout the whole forest (73 stands) or throughout a subset of stands excluding those close to log piles (50 stands)

| Forest management | Observed % of attacked trees | Sampling plans (edges per stand) | Fixed loss of accuracy (Δ) | Minimum sample size | | Sampling effort for 1000 ha | | Bootstrap bias (%) | Accuracy CI% |
|--|------------------------------|----------------------------------|-------------------------------------|---------------------|-----|-----------------------------|-----|--------------------|--------------|
| | | | | S_n | km | km | h | | |
| Forest with logs piles ($n = 73$; km = 125) | 0.35 | Systematic (1) | 0.10 | 41 | 17 | 14 | 0.9 | 0.00 | 1.01 |
| | | | 0.05 | 53 | 22 | 18 | 1.2 | 0.01 | 0.91 |
| | | | 0.01 | 65 | 27 | 22 | 1.5 | 0.01 | 0.84 |
| | | Systematic (All) | 0.10 | 35 | 60 | 49 | 3.3 | 0.01 | 0.71 |
| | | | 0.05 | 51 | 88 | 72 | 4.8 | 0.01 | 0.60 |
| | | | 0.01 | 65 | 112 | 91 | 6.1 | 0.01 | 0.52 |
| | | Adaptive (1 or 2) | 0.10 | 43 | 20 | 16 | 1.1 | −0.03 | 0.87 |
| | | | 0.05 | 57 | 27 | 22 | 1.5 | −0.03 | 0.77 |
| | | | 0.01 | 69 | 32 | 26 | 1.8 | −0.03 | 0.70 |
| | | Adaptive (1 or 3) | 0.10 | 37 | 19 | 16 | 1.0 | −0.07 | 0.77 |
| | | | 0.05 | 49 | 25 | 21 | 1.4 | −0.07 | 0.69 |
| | | | 0.01 | 65 | 34 | 27 | 1.8 | −0.07 | 0.61 |
| | | Adaptive (1 or All) | 0.10 | 33 | 19 | 15 | 1.0 | −0.07 | 0.77 |
| | | | 0.05 | 47 | 27 | 22 | 1.4 | −0.07 | 0.67 |
| | | | 0.01 | 67 | 38 | 31 | 2.1 | −0.07 | 0.59 |
| Forest without logs piles ($n = 50$; km = 85) | 0.24 | Systematic (1) | 0.10 | 23 | 10 | 12 | 0.8 | −0.09 | 0.64 |
| | | | 0.05 | 31 | 13 | 16 | 1.0 | −0.09 | 0.57 |
| | | | 0.01 | 47 | 20 | 24 | 1.6 | −0.09 | 0.48 |
| | | Systematic (All) | 0.10 | 15 | 25 | 30 | 2.0 | −0.07 | 0.50 |
| | | | 0.05 | 23 | 39 | 47 | 3.1 | −0.07 | 0.43 |
| | | | 0.01 | 45 | 76 | 91 | 6.1 | −0.07 | 0.34 |
| | | | | | | | | | |

In systematic sampling plans, the number of edges per stand to be observed was constant (1 or All). In adaptive sampling plans a greater number of consecutive edges were observed if the starting border was in the neighbourhood of a log pile (2, 3 or All). For each sampling plan, the minimum number of stands to be sampled (S_n) is determined according to three fixed levels of accuracy loss compared to the maximum sample size, $\Delta = 0.1$, 0.05 and 0.01% of attacked trees, respectively (see Section 2, Fig. 2). The corresponding length of strips to be observed is presented. This sampling distance was then standardized to a 1000 ha forest and the corresponding duration of observation was calculated for a speed of 15 km/h. Bootstrap bias (BB) is the absolute mean bias expressed in % of attacked trees obtained for the corresponding sample size (S_n). The accuracy presented is the width of the confidence interval (CI 95%) of the mean % of attacked trees per stand (MPAT) achieved for S_n (see Section 2, Fig. 2).

larger bias estimate. By contrast, for a given value of accuracy loss (i.e. $\Delta = 0.05\%$) and a similar sampling effort (around 22 km/1000 ha), adaptive sampling plans were more accurate (ca. 0.6–0.7%) than the systematic samplings involving one edge per stand. Moreover, for a same precision (ca. 0.6–0.7%), adaptive sampling plans were three times less expensive in terms of sampling effort (ca. 1.5 h of observation/1000 ha) than the systematic samplings involving all edges per stand (ca. 4.8 h/1000 ha).

3.4. Effect of the proportion of stands with log piles on damage estimation at the forest level

The number of kilometers to be sampled for each sampling plan was fixed at 22 km/1000 ha, representing ca. 1.5 h of observation through the simulated forests by unbalanced resampling. According to a proportion of stands bordered by a log pile ranging from 0 to 100% the percentage of attacked trees varied from 0.24 to 0.59% in the forests.

Systematic sampling plans showed an increasing estimation bias (from −0.09 to 0.20% of attacked trees) with an increasing proportion of stands bordered by a log pile in the sampled forests (Fig. 5). The response curves of bias against proportion of stands with log piles were similar irrespective of the number of sampled edges (1 or All). The number of stands to be

observed was $S_n = 27$ and 67 for 1 edge/stand and All edges/stand, respectively (it remained constant due to the great number of randomizations).

The response curves of bias against proportion of stands with log piles always showed lower slopes in adaptive than in systematic samplings. A noticeable drop of bias was observed between adaptive plans with the observation of one (“1 or 2”) versus 2 or more (“1 or 3”, “1 or All”) additional stand edges (Fig. 5). In the latter cases, the bias was negative (under-estimation), very low (from −0.08 to −0.04%) and almost independent of the proportion of stands with log piles in the simulated forest. However, in the adaptive sampling schemes, the number of stands to be sampled decreased as the number of stands with log piles increased, due to the higher number of additional edges per stand that would have been sampled. It decreased from 65 down to 48, 38 and 31 stands for the “1 or 2”, “1 or 3” and “1 or All” schemes, respectively.

4. Discussion

4.1. Strip sampling along stand edges

The low levels of attacked trees by *I. sexdentatus* recorded in the study (0.35%) were in accordance with those provided by national and regional post-storm surveys in the same area and

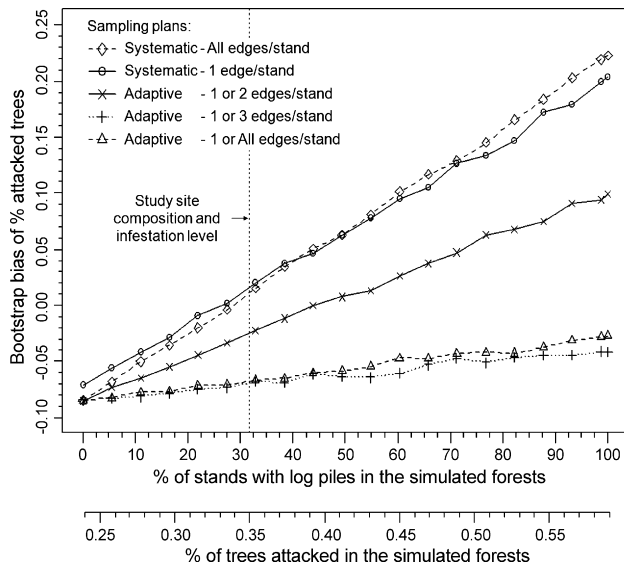


Fig. 5. Relationship between the bootstrap bias (BB) of the percentage of attacked trees and the percentage of stands with log piles in simulated forests, for five roadside sampling plans. For each sampling plan, the number of kilometers to be observed per forest was fixed to 22 km/1000 ha according to Table 3 ($\Delta = 0.05\%$). Stratified bootstrap estimates were computed over 5000 randomizations with replacement for forests of 73 stands with an increasing proportion of stand with log piles (and thus an increasing percentage of attacked trees, as shown on the second axis). The vertical dotted line shows the observed proportion of stands with log piles in the study site in 2001, and the corresponding value of 0.35% attacked trees.

period of time (Nageleisen, 2002; Jactel and Van Halder, 2004). Attacked trees were also irregularly scattered through both stands and landscape, emphasizing the difficulty to sample bark beetle damage over large areas. The spatial occurrence of bark beetles depends on the distribution of suitable breeding material. In theory, a living tree can only be colonised by bark beetles if pioneer insects, releasing aggregation pheromone, are able to recruit a sufficient number of individuals to overwhelm the host trees defences (Hodges et al., 1985; Raffa et al., 1993). The patchy distribution of attacked standing trees by bark beetles, that is often observed following windstorm damage, therefore reflects the uneven distribution of fallen or broken trees on which bark beetles have previously built up their population (Schlyter and Lundgren, 1993; Peltonen et al., 1998; Wichmann and Peter Ravn, 2001; Gilbert et al., 2005; Grodzki et al., 2006). As already observed during several bark beetle outbreaks in the United States (Fettig et al., 2007), piles of cut logs can also play the role of bark beetles refuges when they are stored within the forest. They can concentrate high numbers of emergent beetles that may spill over onto neighbouring standing trees. In our study, aggregates of attacked trees at stand edges are therefore likely to result from after-storm log storage. Forest edges may also induce different microclimatic conditions (e.g. higher wind exposure, warmer temperature, decreased humidity) that could benefit bark beetle survival or fecundity (Peltonen et al., 1997; Peltonen and Heliövaara, 1999; Schroeder and Lindelow, 2002; Hedgren et al., 2003). Nevertheless, despite their proximity to log piles and their beneficial microclimate, stand edges did not show

significantly higher densities of attacked trees than stand interiors. This apparent paradox comes from the mode of calculation of the percent of attacked trees. As the sampled strip along the stand edge is much longer than it is wide, only a small part of the infestation focus may be intercepted by the strip. Dividing numbers of attacked trees by strip areas therefore led to an averaging of infestation levels. As a result, it seems legitimate to use stand edges as sampling units to evaluate the percentage of attacked trees within forest stands.

The strip sampling method relies on two main assumptions. The first postulate is that all individuals (here the attacked trees) within the strip can be counted. Furthermore, it is often recommended to use a strip as wide as possible so as to increase the detection efficiency (e.g. Engeman et al., 2005, for variable area transect sampling). In our case study, we made a field survey to determine the maximum distance at which 100% of attacked trees could be sighted from the forest road (D_{\max}) and showed that it varied with tree density. We also noticed that increasing the width of the strip, i.e. using D_{\max} instead of D_{10} sighting distance, would lead to local overestimation of the percentage of attacked trees. The lowest value of D_{\max} in the forest was 10 m, indicating that in any stand, all attacked trees within 10 m (D_{10}) could be sighted with a probability of detection assumed to equal 100%. These results are in accordance with those provided by Carter (1989) and later by Bulman et al. (1999) who tagged trees to simulate beetle damage in a plantation forest. They showed that during a drive-through survey, the detection probability of target trees drastically declined to only 79 and 63% at 20 and 40 m from the road edge. D_{10} sighting distance was thus chosen as the most appropriate transect width because it offered a good compromise between the probability of damage detection in the strips and the accuracy of damage estimation. This fixed and narrow sighting distance is also more user-friendly because a lower number of attacked trees have to be counted and the exact value of the maximum sighting distance (D_{\max}) has not to be recorded.

The second assumption of the strip sampling method is that the population density to be censused does not vary across space. This hypothesis has been validated in our case study since we could not show any overall difference in attacked tree density between stand and edges (see above and Table 2). However, there were still some cases where the presence of log piles resulted in a local concentration of attacked trees within the neighbouring edge. This situation might have led to an overestimation of the percentage of attacked trees in the corresponding stand. As the strip width was fixed, a way to improve the estimate of percentage of attacked trees at the forest scale is to increase the length of strip to be surveyed. Bulman et al. (1999), revisiting Carter's data (1989), clearly demonstrated that the probability of tagged trees detection would be greatly improved by a denser road network, i.e. by a longer roadside survey. The information that breeding material may concentrate bark beetle attacks led us to further propose adaptive sampling plans in which the prolongation of the roadside survey was conditioned by the presence of a log pile. A higher sampling effort was therefore made in stands bordered

by a log pile; we increased the sampled strip length by sampling additional edges around the same stand.

4.2. Roadside survey

For a forest with no log piles, there was no need to develop adaptive sampling due to the lack of infestation foci. Systematic roadside surveys always underestimated the level of damage probably because attacked trees were rare and not evenly distributed. As expected, the accuracy improved with the sampling effort. For an equal sampling effort, e.g. a same number of kilometers sampled (Table 3, Fig. 5) the bias was lower when all edges were sampled, whereas the accuracy was slightly better when only one edge was sampled. However, results showed no clear evidence that one systematic sampling plan was much better than the other. Foresters could then either decide to sample one edge in many stands or all edges in fewer stands to gain the same estimate of attacked trees by bark beetle infestation during the pre-outbreak phase. However it is not likely that they will be able to drive all around the stands to survey all edges. We would therefore recommend sampling only one edge in a maximum number of stands.

For a forest with log piles, bootstrap resampling showed that the percentage of attacked trees can be highly overestimated when only few edges (Fig. 3) or stands (Fig. 4) are surveyed. This was mainly due to the presence of large patches of attacked trees in stands or edges bordered by a log pile. If these stands represented the main part of the sample, the mean percentage of attacked trees was much higher than the overall value at the forest level. Only the incorporation of more edges or stands could reduce the estimate.

Systematic sampling plans gave the same bias estimate irrespective of the number of edges observed per stand (Table 3, Fig. 5). The accuracy improved with the sampling effort but large number of kilometers of survey were required to gain a sufficient accuracy (Table 3). Another main drawback of these sampling plans is that their bias strongly increased with the proportion of stands with log piles and, thereby, with the number of bark beetles infestation foci (Fig. 5). As already pointed out by Roesch (1993) and Acharya et al. (2000) for forest inventories, our results emphasize the need to modify the sample size when infestations occur in clusters.

Adaptive sampling plans were more efficient and cost effective than systematic plans (Khaemba et al., 2001; Thompson, 2002). For the same estimate accuracy, they were, on average, three times less expensive in terms of sampling effort (Table 3). For the same sampling effort, e.g. 22 km sampled per 1000 ha, the accuracy improved with the number of additional edges sampled when a log pile was sighted. The main advantage of the adaptive plans was to reduce the mean percentage of attacked trees when the presence of a log pile might have led to a large overestimation. Averaging the mean percentage of attacked trees in the following stand edges would therefore lead to decreased estimate values and minimize the risk of overestimation. Furthermore, including not only one but two or more additional edges in the sample increased the chance to get further from the patch of attacked trees and not to intercept a part of it in

the sampled strip. This is the reason why the sampling accuracy improved in adaptive plans when 3 or All edges were sampled and why the bias increased more steadily in adaptive plans with only two edges sampled when increased the proportion of stands with log piles in the forest (Fig. 5).

The adaptive schemes “1 or 3” provided similar bias and accuracy than the “1 or All” plans. As it was shown by Brown and Manly (1998), a major concern when planning an adaptive sampling is that the final sampling effort cannot be predicted in advance. Here, when the same sampling effort in terms of km travelled was previously fixed, the “1 or 3” option implies surveying more stands (e.g. 38 stands as compared to 31 for the “1 or All” plan in a forest composed of 100% log pile stands). This makes it possible to better explore the whole forest and possibly pick up the spatial variability of infestation level. On the other hand, if infestation foci spread out farther leading to larger patches, the sampling plan “1 or All” would likely limit the risk of intercepting parts of these patched in sampled strips, possibly leading to overestimation.

By using an unbalanced bootstrap, we simulated forests as groups of stands of different characteristics and then tested different roadside sampling plans. However, we did not impose any spatial constraints in simulated forests. Yet, it is well known that the spatial arrangement of forest stands may have an effect on the spatial variability of bark beetle infestations (Coulson et al., 1999). The next step would therefore be to simulate more realistic roadside samplings through the real road network topology and the spatial continuity of stands to be surveyed. To our knowledge, the study of Liang et al. (1997) is the only example combining spatial statistics and roadside sampling technique to estimate population density of a forest defoliator (*Lambdina fuscicollis lugubros*). Using variograms they showed a range of 3 km in the spatial correlation of species abundance. The authors proposed to reduce the sampling effort at the local scale and distribute the sampling nodes up to 3 km apart. Another option to improve our adaptive plans could be to keep on intensively sampling stands in the vicinity of log piles but then to further reduce the sampling effort between two hot spots of infestation risk. This approach could even be scaled up at the regional level.

We developed a roadside sampling strategy to estimate bark beetle infestation at a forest scale of ca. 10 km². However, it might be unrealistic to apply the same sampling scheme at the regional level because it is unlikely that foresters can drive thousands of km to survey the whole region. Following the stratified or guided transects sampling approach (Stahl et al., 2000; Ringvall, 2003) the adaptive roadside sampling could be applied to a sub-sample of forest areas previously stratified according to a ranking of potential risk of bark beetle infestation. This ranking could be based on a gradient of wind damage previously mapped by remote sensing (Deshayes et al., 2006) or on information about log piles location provided by loggers.

5. Conclusion

A trait of bark beetles populations is that they are often clustered. We observed that cut pine logs stored along stand

edges increased the probability of a nearby patch of standing trees attacked by *I. sexdentatus* and it is likely to occur again as the post-storm crises become more frequent. We therefore combined the strip sampling with an adaptive strategy. Our results show that adaptive roadside samplings allow quantifying the overall attack level at the forest scale taking into account the local patchiness of damages. They offer a realistic approach because they require a reasonable sampling effort (ca. 2 h to survey 1000 ha in our case study) and they are easy to apply in forests with a dense road network. This study proposed a range of sample sizes and expected accuracy. It enables end-users to choose the optimal roadside survey according to the characteristics of the forest (e.g. density of road-network) and the management objectives (e.g. allowable cost or time of survey). It provides a framework for ongoing practical applications in the field that take into account the spatial arrangement of forest stands and roads, as well as for investigating sampling strategies to survey larger areas.

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