Japan Society of Forest Planning

Article

Adaptive Cluster Sampling in Inventorying Forest Damage by the Common Pine Sawfly (*Diprion pini*)

Mervi Talvitie*, Tuula Kantola*, Markus Holopainen* and Päivi Lyytikäinen-Saarenmaa*

ABSTRACT

Climate change and biological invasions are threats to healthy forest environments throughout the world. Some species that have previously caused only small-scale damage have now become serious pests, causing massive outbreaks and yield losses including in Scandinavia. The spatial scale of outbreaks and intensity of defoliation caused by the common pine sawfly (*Diprion pini* L.) can vary between years, due to fluctuation in population dynamics. The study area is situated in Ilomantsi, eastern Finland, where *D. pini* has caused vast needle losses in managed Scots pine stands. We aimed at developing an accurate and cost-efficient inventory method for insect damage, in which we compared stratified adaptive cluster sampling, random adaptive cluster sampling and simple random sampling. Stratified adaptive cluster sampling proved to be the most accurate method and was a promising candidate for inventorying and monitoring pest insect damage in the study. Adaptive cluster sampling is a promising method for inventorying and monitoring such phenomena when area does not remain constant all the time.

Keywords: adaptive cluster sampling, insect outbreak, defoliation, *Diprion pini*

INTRODUCTION

Climate change has caused rising temperatures throughout the world. Ecological balance has been interrupted, causing among other things pest damage in managed forests (Dale *et al.*, 2001; Evans *et al.*, 2002). The speed of change is higher at higher latitudes, as in Scandinavia. Forest insects, formerly regarded as harmless organisms during recent decades, are now causing serious damage in Finland (Lyytikäinen-Saarenmaa and Tomppo, 2002; de Somviele *et al.*, 2007). Economic losses can be considerable, appr. 300 - 1000 eur ha^{-1}, depending on intensity of needle loss. It can require over a decade for a tree to recover fully (Lyytikäinen-Saarenmaa *et al.*, 2006).

The common pine sawfly (*Diprion pini* L.) (Hymenoptera, Diprionidae) is a univoltine species in Scandinavia. The gregarious larvae actively consume all the needle age-classes of Scots pine (*Pinus sylvestris* L.) during August and September, which could lead to total defoliation of host trees in the climax phase of population dynamics (Viitasaari and Varama, 1987; Geri, 1988). Mature and maturing trees have the highest defoliation risk, but at peak densities seedlings can also suffer from defoliation (Geri, 1988; de Somviele *et al.*, 2004). *Diprion pini* hibernates in the cocoon stage and adult insects emerge early in the season. Diapause is typical for this species, lasting up to several years and prolonging outbreaks. Outbreaks have usually covered only some hundreds or thousands of hectares during the last 150 years, according to published records (e.g. Kangas, 1963; de Somviele *et al.*, 2007). A massive outbreak by *D. pini* occurred on dry and dryish pine forests in central Finland between 1997 and 2001, covering 500,000 ha (Lyytikäinen-Saarenmaa and Tomppo, 2002). The outbreak reached thus Ilomantsi district (eastern Finland) in 1999, where sawfly densities have fluctuated since then, showing a chronic nature.

Monitoring of sawfly outbreaks and defoliation is typically based on field sampling, i.e. collecting different life stages and performing analyses of this material in a laboratory (e.g. Juutinen and Varama, 1986). This kind of monitoring consumes extensive amounts of resources, and results may be biased. The method is still in use at the Finnish Forest Research Institute (Metla). The latest innovation in monitoring is based on semiochemicals, i.e. sex pheromones of sawflies, but

---

Corresponding author: Mervi Talvitie
E-mail: mervi. talvitie@helsinki. fi
*Department of Forest Science, University of Helsinki, P.O. Box 27, 00014 University of Helsinki, Finland

NII-Electronic Library Service

Japan Society of Forest Planning

the method results in population and risk estimates only at the stand level (Lyytikäinen-Saarenmaa *et al.*, 1999; 2006). Furthermore, estimates for forthcoming defoliation and yield losses may be indicative. Metla carries out the National Forest Inventory (NFI) every 10 years, when information on forest health as a side product of permanent and temporary field clusters is also collected at the coarse level (Tomppo *et al.*, 2006). The NFI applies satellite data, e.g. Landsat Thematic Mapper (TM) images, but not for monitoring of forest disturbances. Long inventory periods and sparse layout of clusters result in problems for annual needs of precise information on forest disturbances and risk estimates for the coming years.

Deciding on an optimal inventory method is often the crucial phase for a certain research problem. The natural distribution of ecosystems is fragmented, mainly due to human intervention. Ecological distributions are very rarely randomly distributed (Levin, 1992). With conventional forest inventory methods, large areas must be covered to achieve acceptable precision of rare objects (Green, 1993; Green and Young, 1993). Estimates need to be reliable; imprecise estimates may skew the real situation in the population and result in bad forest management decisions. Thus, prior information on the population of interest is crucial to decision-making (Kangas and Maltamo, 2006).

Adaptive cluster sampling (ACS) was suggested as a method for estimating rare and clustered populations that are difficult to estimate with high accuracy, using conventional sampling methods (Thompson, 1990; 1991; Roesch, 1993; Magnussen *et al.*, 2005). Many studies concerning ACS have been undertaken with simulated data (e.g Roesch, 1993; Brown and Manly, 1998; Brown, 2003; Su and Quinn, 2003; Magnussen *et al.*, 2005). Few ACS studies, to our knowledge, have been done with actual data. Acharya *et al.* (2000) examined the density of three different rare tree species in Nepal with ACS, and Talvitie *et al.* (2006) used ACS in inventorying coarse woody debris in the city forests of Helsinki.

The aim of the present study was to develop an accurate and cost-efficient inventory method for defoliating forest insects. ACS was chosen as the field inventory method. The defoliation estimate and variance of stratified ACS (ACS$_{\mathrm{ST}}$) were compared with those of random ACS (ACS$_{\mathrm{SRS}}$) and simple random sampling (SRS) inventories. ACS$_{\mathrm{ST}}$, ACS$_{\mathrm{SRS}}$ and SRS samples were all based on the same field inventory and sample plots.

SAMPLING THEORY AND DESIGN

In sampling rare clustered phenomena, ACS has the advantage over other, more conventional sampling methods (e.g. Thompson, 1990; Roesch, 1993). The initial set of units is selected, using a probability sampling procedure, and additional units are added to the sample from the neighbourhood of unit i in case the variable of interest (y_i) satisfies a given criterion, i.e. if $y_i \in C$, $C=\{x: x \geq c\}$. prior to sampling. The procedure is repeated until no new additional plots can be found whose variable exceeds the given value. Thus, sampling effort is focused on limited areas with a high number of interesting variables.

The population consists of N units $\{1, 2, \cdots, N\}$ and has variables of interest $y=\{y_1, y_2, \cdots, y_N\}$. In forest applications, a tree or sample plot is normally taken as a basic unit. For every unit i in the population, a physical neighbourhood A_i will be defined that consists of a collection of units that includes unit i. If unit j is in the neighbourhood of unit i, then unit i is also in the neighbourhood of unit j (Thompson, 1990).

A *network* is defined as a group of units whose values are all at least as large as the critical value C. A unit that does not satisfy this condition, but is in the neighbourhood of the unit that does, is referred to as an *edge unit* (Thompson, 1990). A network within its edge units is called a cluster. The difference from conventional sampling designs is that the procedure for selecting an adaptive sample is dependent on the population values observed in the field. The efficiency of the ACS method is dependent on the density and clustering degree, neither of which is known before the initial sampling. All the above-mentioned factors increase the uncertainty in choosing which study method to use in an investigation.

Thompson (1990) presented a modified Horwitz-Thompson

Table 1 Simple random sampling and adaptive cluster sampling estimators and variances applied in the study

Estimator	Mean	Variance
Simple random sampling (SRS)	$\hat{\mu}_{\mathrm{SRS}}=\frac{1}{n}\sum_{i=1}^{n} y_i$	$\mathrm{var}(\hat{\mu}_{\mathrm{SRS}})=\frac{\sum_{i=1}^{n}(y_i-\hat{\mu}_{\mathrm{SRS}})^2}{n-1}$
Adaptive cluster sampling (ACS)	$\hat{\mu}_{\mathrm{ACS}}=\frac{1}{N}\sum_{k=1}^{K}\frac{y_k^*}{\alpha_k}$	$\hat{\mathrm{var}}(\hat{\mu}_{\mathrm{ACS}})=\frac{1}{N^2}\left[\sum_{j=1}^{K}\sum_{k=1}^{K}\frac{y_j^* y_k^*}{\alpha_{jk}}\left(\frac{\alpha_{jk}}{\alpha_j\alpha_k}-1\right)\right]$

N=number of units in the population, n=number of units in the initial sample, K=number of distinct networks represented in the initial sample, y_i=observation in unit i, y^*_k=sum of observations in network k, α_k=the probability that the initial sample intersect network A_k, α_{jk}=the probability that the initial sample includes at least one unit in each of networks j and k.

NII-Electronic Library Service

(HT)-type (Horvitz and Thompson, 1952) estimator designed for unbiased use in the ACS method. The HT estimator is based on the inclusion probabilities obtained from the data (Thompson, 1991). The HT estimator is rather indifferent to population structure (Felix-Medina, 2003) and, therefore, encourages ecologists to use it in calculations (Salehi, 2003).

The probability (α_k) that the initial sample intersects network A_k is defined as

$$\alpha_k = 1 - \binom{N-m_k}{n_1} \Big/ \binom{N}{n_1}, \qquad (1)$$

where n_1 = initial sample size and m_k = the number of units in the network that includes unit k. The probability (α_{jk}) that the initial sample includes at least one unit in each of the networks j and k is defined in Eq. (2).

$$\alpha_{jk} = 1 - \left[\binom{N-m_j}{n_1} + \binom{N-m_k}{n_1} - \binom{N-m_j-m_k}{n_1}\right] \Big/ \binom{N}{n_1}, \qquad (2)$$

where m_j is the number of units in the network that includes unit j. In comparison, the mean value of the SRS estimator is dependent only on the units in the initial sample and does not take into account units added in the second phase.

Stratified sampling is more effective than random or systematic sampling if the study area is not homogenous and the sampling effort is appropriately allocated (Shiver and Borders, 1996). Moreover, stratified sampling with smaller sample size produces an estimate as precise as that obtained in nonstratified sampling, i.e. the same precision can be achieved at lower cost (Shiver and Borders, 1996). First, the population is divided into rather homogenous subpopulations (strata) according to a certain variable, after which sampling is performed in each stratum separately. Thompson (1991) showed that an ACS_{ST} strategy is more accurate than the conventional ACS_{SRS} strategy in spatially clustered populations.

SAMPLING AND MEASUREMENT IN THE FIELD

The study area, Palokangas (62°52' N, 30°56' E), comprises 3,450 ha in the Ilomantsi district, eastern Finland (Fig. 1). The inventory was taken during May and June 2009, before elongation of current shoots. Since *D. pini* larvae cause defoliation in late summer, field measurements and defoliation assessment early in the season represent the defoliation intensity of the previous autumn. The forests in the study area are mainly pure pine stands on dry to dryish soil sites. Young or middle-aged stands are the majority (Table 2); the average age and diameter of the stands in the study area are 53 years and 14.7cm, respectively.

Diprion pini has caused severe defoliation and tree mortality since 1999 in the study area. The common assumption is that the species prefers only mature or maturing Scots pine trees (Geri, 1988; Dajoz, 2000) and pine stands on shallow, infertile and well-drained soils (Larsson and Tenow, 1984; Viitasaari and Varama, 1987; McMillin and Wagner, 1993). In contrast to the results from previous studies in other countries, elevated defoliation has also been found in younger stands in the eastern parts of Finland, without clear evidence for a preference for only well-drained mineral soils (de Somviele *et al.*, 2004).

Table 2 Stand characteristics of the Palokangas study area

Variable	Average	s.d.
D (cm)	14.7	11.5
H (m)	11.6	8.7
V (m^3 ha^{-1})	72.8	71.1
Age (yrs)	53	37
Basal area (m^2 ha^{-1})	13.5	7.7
Trees ha^{-1}	1,394	1,336

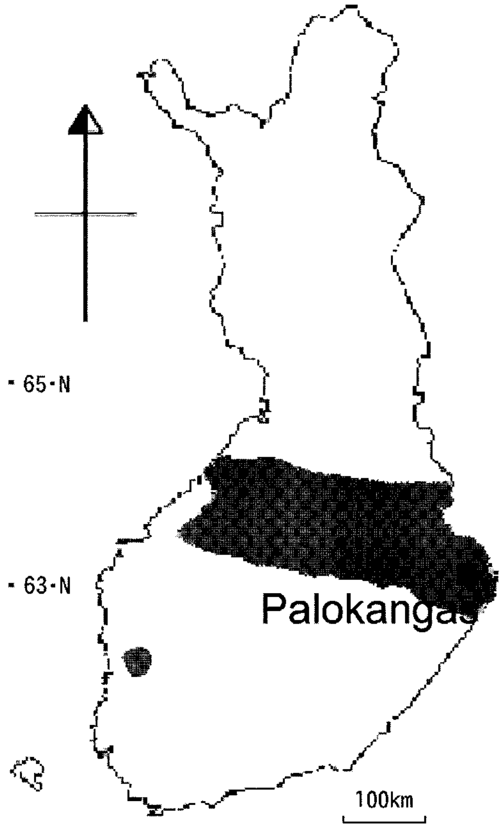

Fig. 1 Location of Palokangas study area. Areas infected by *D. pini* are seen as grey

The sample plots were situated 50 m from each other in the north-south and east-west directions. The position of each plot was obtained with a Trimble GPS Pathfinder Pro XH (Trimble Navigation Ltd., Sunnyvale, CA, USA), which can reach up to 30-cm accuracy. The locations were postprocessed with local base station data, resulting in an average error of app. 1-1.5 m. If a sample plot fell on the border of two stands, it was transferred towards a stand it more belonged to, thus avoiding edge effects. All trees, having a diameter over 5 cm at breast height (1.3 m) were measured, using relascope sample plots (factor $q=1$). For each tree in a sample plot, the species, diameter at breast height, distance and degree from the plot centre were measured. For pines, the defoliation percentage and canopy strata were determined. Every seventh tree of each species was taken as a sample tree. The height of the median trees for each sample plot and the sample trees were determined. Moreover, the age of the stand in a sample plot was determined from the median tree.

The inventory methods used were SRS, ACS_{ST} and ACS_{SRS}. All three methods were based on the initial or total sample plots: SRS only initial sample plots, ACS_{SRS} total sample size without stratification and ACS_{ST} total sample size with stratification. Stratification was performed according to site class and soil type, using the information on compartmentwise inventory, consisting of three strata: 1) high-productivity (HP) class, 2) low-productivity (LP) class, and 3) peatland (Table 3). The HP class contained dryish mineral soil site and sites more fertile than it, and the LP class contained sites poorer than the dryish mineral soil site. The third stratum included peatland plots. Within each stratum, sample plots were chosen, using SRS. There were a total of 55 initial sample plots taken in the sample, representing 0.5% of the total population.

The variable defoliation intensity of a sample plot was taken as the critical variable. Defoliation intensity was an indicator of the former *D. pini* outbreak intensity. The intensity of defoliation of a tree was visually estimated from different directions according to EICHHORN (1998), comparing the tree under investigation to a reference tree with full healthy foliage in the same site type; an accuracy of 10% was used. The defoliation intensity of a sample plot was calculated as the mean value of the defoliation intensity of each tree in the dominant and intermediate crown layers. The underlying trees were omitted from calculation of the plot mean due their limited ability to compete, which could skew the total plot defoliation. The critical value C was 20% in the present study; if the mean defoliation intensity in a sample plot was 20% or more, four additional sample plots were measured north, south, west and east of the unit. The defoliation intensity of 20% can be seen as a threshold value. Intensities less than 20% cause no serious harm to tree increment or mortality; however, a 20% intensity may decrease radial growth by 40-50% after needle consumption by *D. pini* (LYYTIKÄINEN-SAARENMAA *et al.*, 2006).

Table 3 Stratification in numbers within each stratum. Number (n) and percentages (%) of initial plots in the stratum

Stratum	n	%
HL	29	52.7
LP	20	36.4
peatland	6	10.9
total	*55*	*100*

RESULTS

The initial sample consisted of 55 and the total sample of 180 plots. Four additional units were on a road, and two sample plots were impossible to measure due to such narrow stands. There were three clusters in the HP stratum and three clusters in the LP stratum with at least one sample plot having a defoliation intensity over 20% (Table 4). No defoliation rate over 20% was found in the peatland class. The largest cluster, a total of 43 units, was found in HP (Fig. 2). The ACS meth-

Table 4 Clusters in the final sample, number of plots and their defoliation intensity in comparison to the critical value C=20%

Stratum	Cluster	Plots	$C\geq 20\%$	$C<20\%$
HP	1	5	1	4
HP	2	43	20	23
HP	3	21	7	14
LP	4	21	7	14
LP	5	37	14	23
LP	6	5	1	4

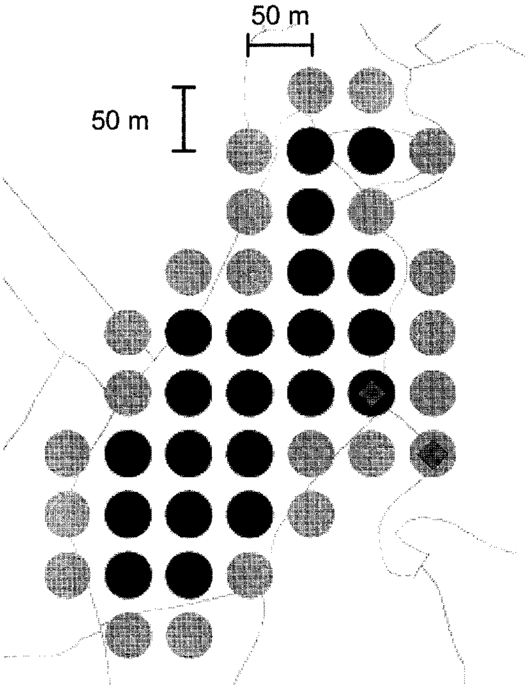

Fig. 2 Arrangement of a cluster. Initial sample plots (dark grey diamond), additional neighbouring plots satisfying the condition $C\geq 20\%$ (black circle) and additional plots, called edge units, with less than 20% defoliation (light grey circle)

Table 5 Number of units in the initial sample(n) and final sample(m), estimates(μ), variances(s^2) and coefficients of variation (CV) in each stratum and in the total population

Method	Stratum	n	m	μ	s^2	CV%
$\mathrm{ACS_{ST}}$	total	55	180	8.3	21.4	55.7
	HP	*29*	*95*	*6.4*	*20.1*	*69.6*
	LP	*20*	*79*	*9.2*	*26.4*	*55.8*
	Peatland	*6*	*6*	*11.4*	*15.6*	*34.6*
$\mathrm{ACS_{SRS}}$	total	55	180	8.3	30.1	66.2
SRS	total	55	55	8.5	109.3	123.2

ods were calculated, using the total sample plots (180 plots), while the SRS calculations were based on the initial sample plots.

The SRS, $\mathrm{ACS_{ST}}$ and $\mathrm{ACS_{SRS}}$ estimators for the defoliation mean and variance were calculated (Table 5). The mean values for all the estimators were very similar: 8.3% using $\mathrm{ACS_{ST}}$ and $\mathrm{ACS_{SRS}}$ to 8.5% using SRS. The mean value represents the mean defoliation index of the total study area. Within $\mathrm{ACS_{ST}}$ strata, the mean values varied between 6.4% in the richest HP soil class and 11.4% in peatland.

The coefficient of variation (CV) describes how much the variation is in relation to the estimate. It is a normalized measure of dispersion of a probability distribution and, thus, offers a way to compare the means and variances of different scales. The CV values are represented as percentages (Table 5). The smallest percentage for CV was found in $\mathrm{ACS_{ST}}$ (55.7%). Again, that of SRS (123.2%) was significantly larger.

DISCUSSION

In inventorying rare and clustered forest phenomena, ACS has been considered as an effective design for estimating density and total amount of the variable of interest (THOMPSON, 1990; 1991). Using ACS, one can focus measurements on areas with high damage intensity. If population groups are larger than sample plots, it is more efficient to measure and estimate the variables of interest using the ACS method (ACHARYA *et al.*, 2000). In many situations, the costs of a unit that do not satisfy the critical value C are lower than those of a plot that do. Moving from one sample plot to another takes time; if the plots are situated near each other the time spent on walking is decreased rapidly. However, one reason why ACS is seldom used in practice is that the sampling size is not known in advance. The risk that the sample size would become too large and thus, time-consuming, can be solved with restricted ACS (BROWN and MANLY, 1998). The restricted design allows the final sample size to be approximately determined before field sampling (BROWN and MANLY, 1998).

Here, the defoliation intensity estimates were quite similar in all sampling methods, which increases the need for careful evaluation of the effectiveness of the methods. The total population variance of $\mathrm{ACS_{ST}}$ was smallest because the sampling method takes into account prior information from the stratification. Both the $\mathrm{ACS_{ST}}$ and $\mathrm{ACS_{SRS}}$ methods allow measurement of additional units; in $\mathrm{ACS_{SRS}}$, the outcome was calculated for the entire sample and the result showed a larger variance. Thus, the influence of prior information is significant. When each stratum is calculated separately, the results achieved are more precise. The SRS variance was nearly twice as large as that of $\mathrm{ACS_{ST}}$ and was not capable of competing with ACS methods for the effectiveness of inventorying insect-caused defoliation. The SRS method suffered from small sample sizes and the loss of taking adaptive measuring units. On the other hand, even if the SRS took the same number of sample plots into calculation, it would suffer from its ineffectiveness.

The CV describes the dispersion of the variable so that the variable's measurement unit is no object. Higher CV implies that there is greater dispersion in the variable. Here, CV also confirms the superiority of $\mathrm{ACS_{ST}}$ in inventorying *D. pini*-caused damage in comparison to $\mathrm{ACS_{SRS}}$ and SRS. The CV% of $\mathrm{ACS_{SRS}}$ was larger to some extent; again, that of SRS was significantly larger.

In $\mathrm{ACS_{ST}}$, comparison between strata shows that peatland had the most homogenous sample plots. There were no seedling plots in the stratum, in which no or only slight defoliation intensity was found. If prior information is available, it is worth considering how to use it best in selecting the initial sample. Our results agree with those of DE SOMVIELE *et al.* (2004) in Palokangas: defoliation is lower in stands situated in more fertile forest site types. The largest cluster was found in the HP stratum, mainly situated in the seedling tree position, where there are appr. 20 trees per hectare. Such low densities can also constitute a risk of defoliation in more fertile productivity stands.

During late summer 2008, *D. pini* defoliation was relatively minor. There were only two plots in the final sample with defoliation intensities over 40%, and most of the initial sample plots had intensities under 20%. *Diprion pini*-caused defoliation has occurred in the Palokangas area for over a decade, fluctuating since that time. If the ACS method is used to inventorying the phenomenon, more sample plots would be measured in years when the defoliation is more intense.

Some of the sources of error in the fieldwork may have included measurement and positioning errors in locating and measuring the relascope sample plot. Yet, the effects of these errors could not be analytically observed in the results. Positioning errors can result in misidentified strata in plots when $\mathrm{ACS_{ST}}$ is used. However, due to the accurate positioning achieved with the global positioning system (GPS) device, there were no such problems in our field measurements.

The above-mentioned source of error can lead to the risk of misidentifying the variable of interest. In SRS, misidentifications may cancel each other, but in adaptive sampling they

Japan Society of Forest Planning

accumulate. Thus, an adaptive sampling method should be employed for variables that can be identified with full confidence. Here, the critical variable was estimated visually, which could easily cause deviation in results if the surveyor were not a professional. Naked-eye calibration is essential when two or more researchers are estimating the critical variable.

Further studies will be focused on acquiring additional information by aerial photographs and laser-scanning data, thus bringing more information to the initial sample selection (Lyytikäinen-Saarenmaa *et al.*, 2008). Remote-sensing materials are valuable means for detecting and mapping insect damage in rare and clustered phenomena. In this study, stratification was performed according to the compartment-wise information from the study area. With remote-sensing data, the stratification could be carried out by focusing on more plots in areas where pest damage could already be detected from the material.

LITERATURE CITED

Acharya, B., Bhattarai, G., de Gier, A. and Stein, A., (2000): Systematic adaptive cluster sampling for thle assessment of rare tree species in Nepal. For. Ecol. Manage. **137**: 65-73

Brown, J.A., (2003): Designing an efficient adaptive cluster sample. Environ. Ecol. Stat. **10**: 95-105

Brown, J.A. and Manly, B.J.F., (1998): Restricted adaptive cluster sampling. Environ. Ecol. Stat. **5**: 49-63

Dajoz, R., (2000): Insects and forests: The role of diversity of insects in the forest environment. Intercept Ltd., London, 668 pp

Dale V.H., Joyce L.A., McNulty S., Neilson R.P., Ayres M. P., Flannican M.D., Hanson P.J., Irland L.C., Lugo A.E., Peterson C.J., Simberloff D., Swanson F.J., Stocks B.J. and Wotton B.M., (2001): Climate change and forest disturbances. Bioscience **51**: 723-734

de Somviele, B., Lyytikäinen-Saarenmaa, P. and Niemelä, P., (2004): Sawfly (Hym., Diprionidae) outbreaks on Scots pine: effect of stand structure, site quality and relative tree position on defoliation intensity. For. Ecol. Manage. **194**: 305-317

de Somviele, B., Lyytikäinen-Saarenmaa, P. and Niemelä, P., (2007): Stand edge effects on distribution and condition of Diprionid sawflies. Agric. For. Entomol. **9**:17-30

Eichhorn, J., (1998): Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests. Part II. Visual assessment of crown condition and submanual on visual assessment of crown condition on intensive monitoring plots. United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution, Germany

Evans, H., Straw, N. and Watt, A., (2002): Climate change: Implication for insect pests. In: Broadmeadow, M. (ed) Climate change: Impact on UK forests. Forestry Commission Bulletin **125**: 99-118

Felix-Medina, M.H., (2003): Asymptotics in adaptive cluster sampling. Environ. Ecol. Stat. **10**: 61-82

Geri, G., (1988): The pine sawfly in central France. In: Berryman, A.A. (ed) Dynamics of forest insect populations: Patterns, causes, implications. Plenum Press, New York: 377-405

Green R.H., (1993): Sampling to detect rare species. Ecol. Appl. **3**:351-356

Green, R.H. and Young, R.C., (1993): Sampling to detect rare species. Ecol. Appl. **3**: 351-356

Horvitz, D.G. and Thompson, D.J., (1952): A generalization of sampling without replacement from a finite universe. J. Am. Stat. Assoc. **47**: 663-685

Juutinen, P. and Varama, M., (1986): Occurrence of the European pine sawfly (Neodiprion sertifer) in Finland during 1966-83. Folia For. **662**: 1-39 (in Finnish with an English summary)

Kangas, E., (1963): Über das Schädliche Auftreten der Diprion-Arten (Hym., Diprionidae) in finnischen Kiefernbeständen in diesem Jahrhundert. Z. Angew. Entomol. **51**: 188-194 (in German)

Kangas, A. and Maltamo, M., (eds) (2006): Forest inventory: methodology and applications. Mapping forest ecosystems. Vol 10. Springer, Dordrecht, 362pp

Larsson, S. and Tenow, O., (1984): Areal distribution of a Neodiprion sertifer (Hym., Diprionidae) outbreak on Scots pine as related to stand condition. Holarct Ecol. **7**: 81-90

Levin, S.A., (1992): The problem of pattern and scale in ecology. Ecology **73**: 1943-1967

Lyytikäinen-Saarenmaa, P., Anderbrant, O., Löfqvist, J., Hedenström, E. and Högberg, H.E., (1999): Monitoring the European pine sawfly population densities with pheromone traps in young pine plantations. For. Ecol. Manage. **124**: 113-121

Lyytikäinen-Saarenmaa, P., Holopainen, M., Ilvesniemi, S. and Haapanen, R., (2008): Detecting pine sawfly defoliation by means of remote sensing and GIS. Forstschutz Aktuell **44**: 14-15

Lyytikäinen-Saarenmaa P. and Tomppo E., (2002): Impact of sawfly defoliation on growth of Scots pine Pinus sylvestris (Pinaceae) and associated economic losses. Bull. Entomol. Res. **92**: 137-140

Lyytikäinen-Saarenmaa, P., Varama, M., Anderbrant, O., Kukkola, M., Kokkonen, A.M., Hedenström, E. and Högberg, H.E., (2006): Monitoring the European pine sawfly in maturing Scots pine stands with pheromone traps. Agric. For. Entomol. **8**: 7-15

Magnussen, S., Kurz, W. and Leckie, D. G., (2005): Adaptive cluster sampling for estimation of deforestation rates. Eur. J. Forest. Res. **124**: 207-220

McMillin, J.D. and Wagner, M.R., (1993): Influence of stand characteristics and site quality on sawfly population dynamics. In: Wagner, M. R. and Raffa, K. F. (eds) Sawfly life history - Adaptations to woody plants. Academic Press, San Diego: 334-361

NII-Electronic Library Service

ROESCH, F.A. JR., (1993): Adaptive cluster sampling for forest inventories. For. Sci. **39**: 655-669

SALEHI, M.M., (2003): Comparison between Hansen-Hurwitz and Horvitz-Thompson estimators for adaptive cluster sampling. Environ. Ecol. Stat. **10**: 115-127

SHIVER, B.D. and BORDERS, B.E., (1996): Sampling techniques for forest resource inventory. Wiley, New York, 356pp

SU Z.M. and QUINN T.J., (2003): Estimator bias and efficiency for adaptive cluster sampling with order statistics and a stopping rule. Environ. Ecol. Stat. **10**: 17-41

TALVITIE, M., LEINO, O. and HOLOPAINEN, M., (2006): Inventory of sparse forest inventories using adaptive cluster sampling. Silva Fenn. **40**(1): 101-108

THOMPSON, S.K., (1990): Adaptive cluster sampling. J. Am. Stat. Assoc. **85**(412): 1050-1059

THOMPSON, S.K., (1991): Stratified adaptive cluster sampling. Biometrika **78**(2): 389-397

TOMPPO, E., (2006): The Finnish national forest inventory. In: KANGAS, A. and MALTAMO, M. (eds) Forest inventory: Methodology and applications. Managing Forest Ecosystems. Vol 10. Springer, Dordrecht: 179-194

VIITASAARI, M. and VARAMA, M., (1987): Sawflies 4. Conifer sawflies (Diprionidae). University of Helsinki. Department of Agricultural and Forest Zoology. Reports **10**: 1-79 (in Finnish with an English summary)

(Received 23 September 2009)
(Accepted 24 March 2010)