Climate Change and the Risks of *Neodiprion sertifer* Outbreaks on Scots Pine

Tarmo Virtanen, Seppo Neuvonen, Ari Nikula, Martti Varama and Pekka Niemelä

Virtanen, T., Neuvonen, S., Nikula, A.,Varama, M. & Niemelä, P. 1996. Climate change and the risks of *Neodiprion sertifer* outbreaks on Scots pine. Silva Fennica 30(2–3): 169–177.

The European Pine Sawfly (*Neodiprion sertifer*) is one of the most serious defoliators of Scots pine in northern Europe. We studied the pattern in the regional occurrence of the outbreaks of *N. sertifer* in Finland in years 1961–90, and made predictions about the outbreak pattern to the year 2050 after predicted winter warming. We tested whether minimum winter temperatures and forest type and soil properties could explain the observed outbreak pattern. We analysed outbreak patterns at two different spatial levels: forest board- and municipal-level. The proportion of coniferous forests on damage susceptible soils (dry and infertile sites) explained a significant part of the variation in outbreak frequency at small spatial scale (municipalities) but not at large spatial scale (forest boards). At the forest board level the incidence of minimum temperatures below –36 °C (= the critical value for egg mortality) explains 33 % of the variation in the outbreak pattern, and at the municipal level the incidence of cold winters was also the most significant explaining variable in northern Finland. Egg mortality due to cold winters seems to be the most parsimonious factor explaining why there have been so few *N. sertifer* outbreaks in northern and northeastern Finland. We predict that climate change (increased winter temperatures) may increase the frequency of outbreaks in eastern and northern Finland in the future.

Keywords Scots pine, *Neodiprion sertifer*, insect outbreaks, climate change, cold tolerance, GIS

Authors' addresses *Virtanen* and *Neuvonen*, Department of Biology and Kevo Subarctic Research Station, University of Turku, FIN-20014 Turku, Finland; *Nikula*, Finnish Forest Research Institute, Rovaniemi Research Station, PO Box 16, FIN-96301 Rovaniemi, Finland; *Varama*, Finnish Forest Research Institute, Vantaa Research Centre, PO Box 18, FIN-01301 Vantaa, Finland; *Niemelä*, Faculty of Forestry, University of Joensuu, PO Box 111, FIN-80101 Joensuu, Finland **Fax** to Virtanen +358 2 333 6550
E-mail tarvirt@sara.utu.fi

Accepted May 24, 1996

1 Introduction

A predicted increase in temperature with accompanying changes in precipitation will have profound consequences for ecosystems (Graham and Grimm 1990, Oechel and Vourlitis 1994). Herbivorous insects will be subject to indirect effects of climate change on the trophic level above and below, as well as to direct effects (Martinat 1987, Solbreck 1990, Williams and Liebhold 1995). Climate change may alter the dynamics of outbreak species in time and space, changing the freqency of outbreaks and their spatial patterns, size, and geographical range (Williams and Liebhold 1995). Generally, populations are expected to extend their ranges to higher latitudes and elevations as climate warms (Solbreck 1990, Williams and Liebhold 1995).

The European Pine Sawfly, *Neodiprion sertifer* (Geoffroy) (Hymenoptera: Diprionidae) is one of the most serious defoliators of Scots pine (*Pinus sylvestris* L.) in northern Europe. Local, isolated mass-occurrences occur almost every year in Fennoscandia. Sometimes they spread into regional outbreaks (Juutinen 1967, Larsson and Tenow 1984, Juutinen and Varama 1986). This defoliating insect can be important on a regional scale in boreal forests as a controller of primary productivity, carbon budgets, and nutrient cycling. Thus, in addition to responding to climate change it also feeds back to global change.

Our aim is to analyse the regional occurrence of the outbreaks of *N. sertifer* in 1961–90 in Finland, and test whether winter minimum temperatures (Neuvonen 1992) and forest type and soil properties (Larsson and Tenow 1984, Juutinen and Varama 1986) can explain the observed pattern. Furthermore, we present a conjectural prediction how climate change (increased winter temperatures in the future) may affect the frequency and regional occurrence of these outbreaks.

In the analyses we concentrate on explanatory variables with close connection to some mechanistic processes known and/or suggested to be important for the population dynamics of *N. sertifer*: 1) *N. sertifer* overwinters in the egg stage. The critical temperature for the death of *N. sertifer* eggs is about –36 °C (Sullivan 1965, Juutinen 1967, Austarå 1971). 2) Outbreaks are known to occur mainly on dry or dryish infertile mineral soil sites (Larsson and Tenow 1984, Juutinen and Varama 1986); mechanisms may involve both host quality and natural enemies (Hanski 1987, Mattson and Haack 1987, Saikkonen and Neuvonen 1993).

2 Material and Methods

We analysed outbreak patterns at two different spatial levels: 1) Forest boards: Finland has been divided into 19 forest boards (459 municipalities in total). Mean yearly proportion of outbreak municipalities from all forest boards municipalities was used as the response variable. This was calculated over the whole study period (1961–90). 2) Municipalities: Number of years with *N. sertifer* outbreaks per municipality in years 1961–90 was the response variable. All the cases in which densities of larvae were clearly higher than in latent populations or *N. sertifer*-damaged pines were observed are classified as outbreaks. Latent populations are very sparse and larval groups can be observed only rarely (Hanski 1987). Consequently, there is no risk that a latent population would be classified as outbreak. The observations were made by forest owners and forest authorities as well as by the Finnish Forest Research Institute (more about outbreak-data and collecting method: Juutinen 1967, Juutinen and Varama 1986).

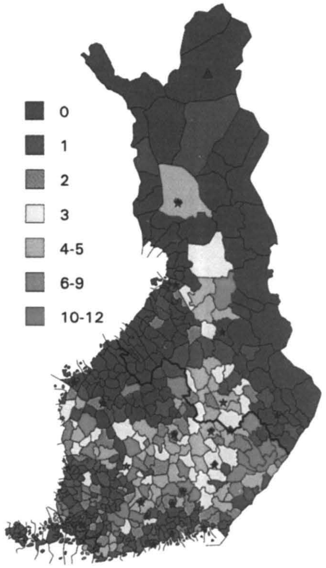

Fig. 1. Number of the years with *N. sertifer* outbreaks in 1961–90. Based on published and unpublished yearly collected information by the Finnish Forest Research Institute; municipalities as observation units. Stars = major cities, omitted from the analysis, triangle = Saariselkä, omitted from the analyses (see text), bold line = line between southern and northern part (see text).

Fig. 2. Mean minimum winter temperatures 1960–90. Grid size 10 km. Source: The Finnish Meteorological Institute.

In the forest board-level analysis we used the following explanatory variables: 1) incidence of (absolute) minimum temperatures below –36 °C (= COLD), 2) percentages of damage-susceptible area (= SOIL; see below), 3) number of municipalities in forest board (= MUNICIPAL). In the municipality level analysis the explanatory variables were: 1) incidence of (absolute) minimum temperatures below –36 °C (= COLD), 2) percentage of damage susceptible area (= SOIL), 3) size of the municipality (values in km^2, = AREA). We used logarithmic transformation in the size of the municipality values to normalize their distribution. At the municipality level we analysed data in two ways: as a whole or divided into the southern and northern part (see Fig. 1). Stepwise regression analysis (SAS user's... 1985) was used at both spatial levels.

We used the databases in Arc/Info geographic information system. The explanatory variables are in grid-format. As outbreak data observation units are municipalities (or forest boards), we calculated and used municipality- and forest-board-means of explanatory variables in analyses.

The incidence of (absolute) minimum temperatures below –36 °C was calculated for every grid cell as a proportion of winters with minimum temperatures below the threshold during 1960–1990. The southern populations seem to be more susceptible to cold than the northern populations (Sullivan 1965, Juutinen 1967, Austarå 1971). We took value –36 °C as a representative for Finnish populations. Mean of the winter minimum temperatures during 1960–90 in different parts of the Finland is shown in Fig. 2.

Both Larsson and Tenow (1984) and Juutinen and Varama (1986) state that *N. sertifer* outbreaks occur mainly on dry or dryish infertile mineral soil sites. On the basis of land use and forest classification, and soil type data we classified coniferous forests growing on dry and dryish sites as potentially damage-susceptible areas and calculated the mean percentage of damage susceptible area (in relation to total land area; Fig. 3)). The soil type classification has the following categories (those in *italics* were considered as 'potentially damage-susceptible'): basal till; *bedrock terrain*; hummocky moraine; *eskers, deltas, ice marginal and interlobate formations; boulder fields; valley trains and other extramarginal deposits*; fluvial deposits; clay deposits; littoral deposits; peat deposits.

We omitted from the analyses major cities (Fig. 1), and observations from the Saariselkä-

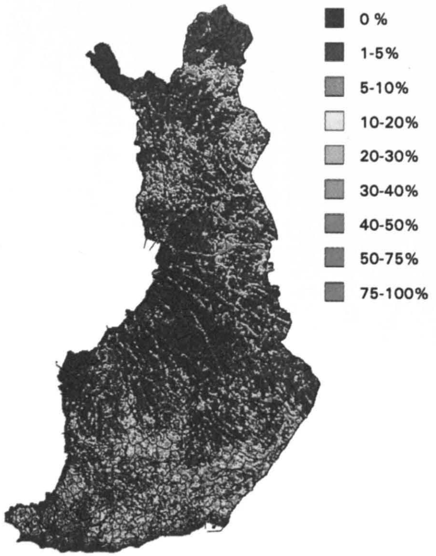

Fig. 3. Percentage of damage susceptible areas from the whole land area, based on forest classification (satellite image based land use and forest classification; grid size 200 m, source National Land Survey of Finland) and soil type (grid size 200 m, based on 1:1 000 000 map, source Geological Survey of Finland).

area (Fig. 1), because outbreaks there situated in mountainous area (Juutinen 1967, Niemelä et al. 1987) and the minimum temperature data is not representative for that site due to temperature inversion. Initial screening of the data showed also that *N. sertifer* outbreaks have been rare in coastal areas (Fig. 1). Since we do not have at present any mechanistic explanation for this pattern we excluded coastal areas (municipalities with seashore) from subsequent analyses.

We made our future predictions for the year 2050 with SILMUSCEN policy scenario (Central), which is recommended as the "best guess" scenario for the project SILMU (= The Finnish Research Programme on Climate Change; Carter et al. 1995). This scenario predicts that mean winter temperature increase is +3.6 °C over 1990–2050 (Carter et al. 1995). Predictions for outbreak pattern were made by regression model equation (Table 1), using minimum temperature incidencies in 2050 in the place of 1960–90 incidencies. Since the SILMU scenarios do not offer information about possible changes in climate variability (Carter et al. 1995) we have to make the most parsimonious assumption of no change in variability which automatically alters the probability of extreme events. We added +3.6 °C to the years 1960–90 minimum temperature data and calculated the incidencies of minimum temperatures below –36 °C at year 2050.

3 Results

The outbreaks of *N. sertifer* were most common in the inland areas of Southern and Central Finland with usually three to nine outbreak years during the period 1961–1990 (Fig. 1). The proportion of forest area dominated by Scots pine is highest in northern Finland and coastal areas (Yearbook... 1994) and so the abundance of Scots pine does not explain the distribution of damage at all.

At the forest board level the incidence for minimum temperatures below –36 °C explains 33 % of the variation in the proportion of municipalities with *N. sertifer* outbreaks (Table 1, Fig. 5a). Also the number of municipalities per forest board explains significant proportion (18 %) of variation (Table 1). This may be due to a mere technical reason: the number of municipalities is used as a divisor when calculating the response variable. At the forest board level the proportion of coniferous forests on damage-susceptible soils does not explain the occurrence of outbreaks (Table 1).

There have been only a few outbreaks in municipalities where the incidence for minimum temperatures below –36 °C has been higher than 0.35 (Fig. 4). At the municipal level, in the regression analysis of the whole country, the incidence of minimum temperatures below –36 °C is the best explanatory variable for variation in outbreak frequency in years 1961–90 (10 %, Table 2a), and the second best explanator is the percentage of damage-susceptible area (7 %, Table 2a). Also, the size of the municipality (more outbreaks in bigger municipalities) explains a significant part of the

Table 1. Regression model at forest board level.

Dependent variable: Mean proportion of outbreak municipalities/year/forestry board. N = 17.

Step	Variable entered	Partial R^2	Model R^2	F	Prob > F	Range of variable
1	COLD	0.3288	0.3288	7.3481	0.0161	0.022–0.668
2	MUNICIPAL	0.1782	0.5070	5.0602	0.0411	6–30
Variable not included in to the model:						
	SOIL	0.0085	0.5155	0.2283	0.6407	1.52–14.24

Equation: 0.1788 – (0.2257 × COLD) – (0.00350 × MUNICIPAL)

Table 2. Regression models at municipal level.

Dependent variable: Number of outbreak years/municipality 1961–90

a) Finland as a whole (N = 342):

Step	Variable entered	Partial R^2	Model R^2	F	Prob > F	Range of variable
1	SOIL	0.0682	0.0682	24.87	0.0001	0–29.34
2	Log(AREA)	0.0235	0.0916	8.75	0.0033	1.48–4.10
3	COLD	0.0991	0.1907	41.40	0.0001	0–0.90

Equation: –4.284 – (6.936 × COLD) + (0.0807 × SOIL) + (2.455 × Log(AREA))

b) Southern Finland (N = 224):

Step	Variable entered	Partial R^2	Model R^2	F	Prob > F	Range of variable
1	Log(AREA)	0.1304	0.1304	33.30	0.0001	1.49–3.20
2	SOIL	0.0460	0.1764	12.34	0.0005	0.40–29.34
Variable not included in to the model:						
	COLD	0.0060	0.1824	1.60	0.2067	0–0.23

Equation: –5.256 + (0.0949 × SOIL) + (2.606 × Log(AREA))

c) Northern Finland (N = 118):

Step	Variable entered	Partial R^2	Model R^2	F	Prob > F	Range of variable
1	COLD	0.1174	0.1174	15.43	0.0001	0.07–0.90
2	SOIL	0.0586	0.1760	8.18	0.0050	0–19.9
3	Log(AREA)	0.0485	0.2245	7.13	0.0087	2.08–4.10

Equation: –1.971 – (7.386 × COLD) + (0.144 × SOIL) + (1.678 × Log(AREA))

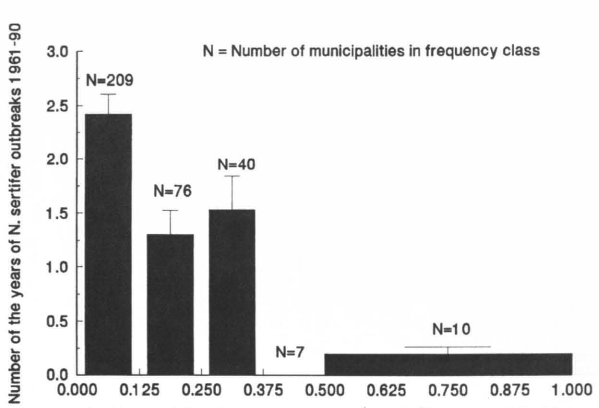

Fig. 4. Number of the years of *N. sertifer* outbreaks/municipality in years 1961–90 in relation to incidence of the winter temperatures below –36 °C.

variation. However, the explanatory power of this model is not very high, only 19 % (Table 2a).

When the analysis is made separately for southern and northern Finland, results are different. In the southern municipalities the best explanator is the size of the municipality (13 % of variation), and also the percentage of damage-susceptible area is significant (Table 2b). In southern Finland, the incidence of minimum temperatures below –36 °C does not explain the number of the outbreaks (Table 2b). However, in northern Finland the incidence of minimum temperatures below –36 °C is the most significant explanator (12 % of variation), and also the damage-susceptible forest area and the size of the municipality are significant explanators (Table 2c).

When the predicted changed winter minimum temperatures are applied to the regression model at forest board level (Table 1), the model predicts more outbreaks/year in the future in eastern and northern forest boards (cf. Figs. 5a and 5b). Due to the generally very low explanatory power of municipality level regression models (Table 2a,b,c) and the apparent non-linearity between the number of outbreak years and the incidence of cold winters (Fig. 4) we do not find it feasible to use the regression model(s) in Table 2 for predicting outbreaks in 2050.

4 Discussion

In 1961–90 *N. sertifer* outbreaks were common in southern Finland but almost lacking in northern and north-eastern parts of the country (with the exception of Saariselkä, see below). The incidence of minimum winter temperatures colder than –36 °C explains well this distribution pattern. There is good evidence that temperature is critical for the survival of eggs (Sullivan 1965, Juutinen 1967, Austarå 1971). There are also reports of collapse of *N. sertifer* outbreaks after cold winters (Juutinen 1967).

Obviously, some other climatic parameters show the same geographic pattern as minimum winter temperatures, e.g. temperature sums are low in northern and northeastern Finland. However, there is no well understood mechanism that might connect low temperature sums with the lack of *N. sertifer* outbreaks. In fact, in Saariselkä (northern Finland, see Fig. 1) the outbreaks occur mainly at the top of the fjells with lowest temperature sum but with mildest winters (Niemelä et al. 1987, Niemelä et al. unpublished). So, we consider egg mortality in cold winters the most parsimonious factor explaining why there have been so few outbreaks in northern and north-eastern Finland.

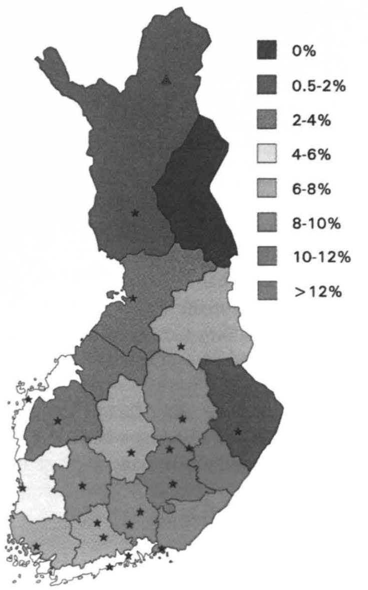

Fig. 5a. Mean percentage of outbreak municipalities per year in forestry boards in Finland in 1961–90. Legend values are upper limits.

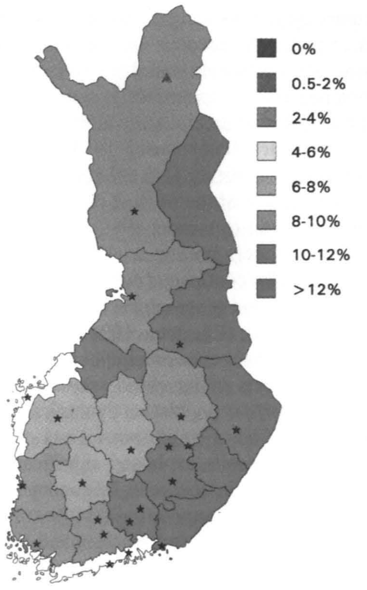

Fig. 5b. Predicted (see text) mean percentage of outbreak municipalities per year in forestry boards in Finland in year 2050. Legend values are upper limits.

Egg mortality is known to be of great significance determining the areal distribution of outbreaks in Autumnal moth, *Epirrita autumnata* (Bkh) (Tenow and Nilssen 1990). During temperature inversions in winter cold air accumulates to lower areas, and the temperature differences can be over 10 °C just within few square kilometres (Tammelin 1988, Tenow and Nilssen 1990). Modelling local, topographic variation in minimum winter temperatures is necessary when studying the population dynamics of *E. autumnata* (T. Virtanen, S. Neuvonen and A. Nikula, unpublished observations) and also when aiming at more accurate predictions of *N. sertifer* outbreaks in northern Finland in the future.

The climatic models predict areal differences in the increase of winter temperatures in Finland. Models GFDL and UKMO predict less increase into northern Finland than in southern Finland, and ECHAM1 the opposite (Carter et al. 1995). According to Räisänen (1994) the most realistic winter temperatures in northern Europe are given by the GFDL simulations. If climate warming will happen according to GFDL simulation, then SILMU policy scenario value which we used in our predictions (+3.6 °C increase) could be too high for northern Finland. However, the minimum winter temperatures occur during temperature inversions (clear calm periods). There are also predictions of increase in winter precipitation (Räisänen 1994, Carter et al. 1995), which possibly will result in rarer inversions. This, in turn, could lead to a larger increase in minimum temperatures than in mean temperatures (see also, Karl et al. 1995).

There are also connections between precipitation and population dynamics of *N. sertifer*. It has been hypothesized that drought periods can be the triggering factor which releases an outbreak, either through changes in needle chemistry (Larsson and Tenow 1984) or in cocoon predation (Hanski 1987). Predation of pine sawfly cocoons by shrews can be one of the most important factors in keeping the population levels below the outbreak numbers (Hanski and Parviainen 1985, Hanski 1987), and it is known that high summer precipitation affects positively shrew densities (Pankakoski 1985). Precipitation and high moisture also enhance the dispersal and infection of the nuclear polyhedrosis virus of *N. sertifer* (Olofsson 1988).

Climate models predict a slight increase in precipitation for continental northern Europe, but seasonal cycle and geographical details vary from model to model (Räisänen 1994, Carter et al. 1995). Thus, changes in precipitation may counteract the effects of increased winter temperatures on *N. sertifer* population dynamics.

The proportion of coniferous forests on damage-susceptible soils explained significant part of the variation in outbreak frequency at the municipal level thus supporting the ideas of Larsson and Tenow (1984) and Juutinen and Varama (1986). The proportion of damage susceptible forest did not emerge as a significant explanatory variable in the forest board level analysis. This may be either because the range of variation in the explanatory variable was smaller with forest boards than with municipalities, or because other (here unstudied) explanatory variables masked its effects at the more robust spatial scale.

We see a need to further develop the damage susceptibility index by considering especially: 1) Age structure of forests (which is actually changing): young 20–40 year old stands seem to be most vulnerable (Juutinen 1967, Larsson and Tenow 1984); 2) Better quality soil type, land use, and forest classification data should be used, and also include as susceptible certain types of pine bogs where outbreaks have been reported (Juutinen and Varama 1986).

In the future, the following aspects should also be taken into account: 1) In Finland the nuclear polyhedrosis virus has been used to control *N. sertifer* outbreak's since year 1972 (Juutinen and Varama 1986). This has changed locally the severity, areal distribution, and duration of outbreaks during the later part of our analysis period. 2) For some of the outbreak periods all the pre- and postgradation years are not recorded, as an outbreak usually lasts at least 2 to 3 years (Juutinen 1967, Larsson and Tenow 1984, Juutinen and Varama 1986, Hanski 1987).

Our prediction that *N. sertifer* outbreaks will be more probable in the northern Finland in the future (year 2050; Fig. 5b) should be considered with some caution because the basic mechanism (winter mortality of eggs) used in the prediction is asymmetric in a causal sense. Very cold winters are sufficient to prevent the outbreaks of *N. sertifer* but the lack of eggs-killing temperatures are, on the other hand, a necessary but not sufficient condition for the occurrence of outbreaks. Thus, for predicting increased outbreak risks in northern Finland as a consequence of warming (winter) climate we have to make the additional assumption that the other factors controlling *N. sertifer* population dynamics behave essentially as they do in southern Finland at present.

Acknowledgements

We thank Jari Kouki, Irma Saloniemi, and two anonymous referees for comments on the manuscript, and SIPATI-project for databases. Marja Vieno checked the English. The study was financed by the Academy of Finland (SILMU, Finnish Research Programme on Climate Change).

References

Austarå, Ö. 1971. Cold hardiness in eggs of Neodiprion sertifer (Geoffroy) (Hym., Diprionidae) under natural conditions. Norsk Entomologisk Tidsskrift 18: 45–48.

Carter, T., Posch, M. & Tuomenvirta, H. 1995. Silmuscen and cligen. Guidelines for the construction of climatic scenarios and of a stochastic weather generator in the Finnish research programme on climate change (SILMU). Publications of the Academy of Finland 5/95.

Graham, R. W. & Grimm, E. C. 1990. Effects of global climate change on the patterns of terrestrial biological communities. TREE 5: 289–292.

Hanski, I. 1987. Pine sawfly population dynamics: patterns, processes, problems. Oikos 50: 327–335.

— & Parviainen, P. 1985. Cocoon predation by small mammals, and pine sawfly population dynamics. Oikos 45: 125–136.

Juutinen, P. 1967. Zur Bionomie und zum Vorkommen der roten Kiefernbuschhornblattwespe (Neodiprion sertifer Geoffr.) in Finnland in den Jahren 1959–65. Communications Instituti Forestalis Fenniae 63(5). 129 p.

— & Varama, M. 1986. Occurrence of the European pine sawfly (Neodiprion sertifer) in Finland during 1966–83 (in Finnish with an English summary). Folia Forestalia 662. 39 p.

Karl, T.R., Knight, R.W. & Plummer, N. 1995. Trends in high-frequency climate variability in the twentieth century. Nature 377: 217–220.

Larsson, S. & Tenow, O. 1984. Areal distribution of a Neodiprion sertifer (Hym., Diprionidae) outbreak on Scots pine as related to stand condition. Holarctic Ecology 7: 81–90.

Martinat, P.J. 1987. The role of climatic variation and weather in forest insect outbreaks. In: Barbosa, P. & Schulz, J. (eds.). Insect outbreaks. Academic Press, New York. p. 241–268.

Mattson, W.J. & Haack, R.A. 1987. The role of drought stress in outbreaks of plant-eating insects. BioScience 37: 110–118.

Neuvonen, S. 1992. Anthropogenic environmental changes and the risks of forest insect outbreaks. Publications of the Academy of Finland 3/92: 269–273.

Niemelä, P., Rousi, M. & Saarenmaa, H. 1987. Topographical delimitation of Neodiprion sertifer (Hym., Diprionidae) outbreaks on Scots pine in relation to needle quality. Journal of Applied Entomology 103: 84–91

Oechel, W. C. & Vourlitis, G. L. 1994. The effects of climate change on land-atmospheric feedbacks in arctic tundra regions. TREE 9: 324–329.

Olofsson, E. 1988. Dispersal of the nuclear polyhedrosis virus of Neodiprion sertifer from soil to pine foliage with dust. Entomologia Experimentalis et Applicata 46: 181–186.

Pankakoski, E. 1984. Relationships between some meteorological factors and population dynamics of Sorex araneus L. in southern Finland. Acta Zoologica Fennica 173: 287–289.

Räisänen, J. 1994. A comparison of the results of seven CGM experiments in northern Europe. Geophysica 30: 3–30.

Saikkonen, K. & Neuvonen, S. 1993. European pine sawfly and microbial interactions mediated by the host plant. In: Wagner, M.R. & Raffa, K.F. (eds.). Sawfly life history adaptations to woody plants. Academic Press, Orlando. p. 431–450.

SAS user's guide statistics. 1985. 5th edition. SAS Institute Inc., Cary NC.

Solbreck, C. 1991. Predicting insect faunal dynamics in a changing climate – a north European perspective. In: Oechel, W.C. (ed.). Book emonating from symposium "Impact of climatic change on natural ecosystems", Trondheim 27–29 Nov. 1990.

Sullivan, C.R. 1965. Laboratory and field investigations on the ability of eggs of the European pine sawfly, Neodiprion sertifer (Geoffroy) to withstand low winter temperatures. The Canadian Entomologist 97: 978–993.

Tammelin, B. 1988. Orografian aiheuttamista pienilmastollisista eroista Saariselän alueella. Ilmatieteen laitos, Meteorologisia julkaisuja 7. 67 p.

Tenow, O. & Nilssen, A. 1990. Egg cold hardiness and topoclimatic limitations to outbreaks of Epirrita autumnata in northern Fennoscandia. Journal of Applied Ecology 27: 723–734.

Williams, D.W. & Liebhold, A.M. 1995. Forest defoliators and climate change: potential changes in spatial distribution of outbreaks of Western spruce budworm (Lepidoptera: Torticidae) and Gypsy moth (Lepidoptera: Lymantriidae). Environmental Entomology 24: 1–9.

Yearbook of forest statistics 1993–94. 1994. Finnish Forest Research Institute. 348 p.

Total of 25 references