Growth Responses and Mortality of Scots Pine (*Pinus sylvestris* L.) after a Pine Sawfly Outbreak

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Abstract - The focus of this study has been to provide estimates of growth losses and tree mortality after an outbreak by the large pine sawfly *Diprion pini* (L.) and preliminary estimates of the economic value of losses. The study was carried out in SW Finland. Increment cores were sampled for radial growth measurements from trees subjected to slight, moderate and heavy defoliation. Tree mortality during the recovery period was estimated for three different hierarchy positions of trees; hold-overs, dominants and intermediates.

I. Introduction

The primary effects of diprionid sawflies feeding on Scots pine *Pinus sylvestris* (L.) are reductions in tree growth and individual tree mortality. Defoliation affects tree growth in different ways according to the timing, defoliation intensity, length of consumption period, and age of foliage. Reduced stand productivity negatively affects monetary values. Generally, there is a positive relationship between the amount of remaining needles and tree volume increment [1, 2]. Comprehensive studies on the increment losses by the large pine sawfly *Diprion pini* (L.) (Hymenoptera: Diprionidae) are remarkably few in Scandinavia, even if the amount of losses constitute one of the main questions in forest protection [3, 4, 5, 6]. In the Netherlands decreases in radial increment were 57–60% after severe needle damage [7]. According to [5], losses of more than 90% in radial growth can happen if defoliation extends at least two years. Heavy needle damage can in extreme cases result in missing annual rings. Defoliation by *D. pini* causes higher losses than consumption by early season feeders, e.g. the European pine sawfly *Neodiprion sertifer* (Geoffr.) [8, 9, 10, 6]. Defoliation early in the season seldom causes tree mortality, whereas the proportion of tree mortality is much higher after late season feeding, particularly if an outbreak continues at least two years. Tree mortality in a stand defoliated by *D. pini* has been recorded to be approximately 2–3% after a single-year outbreak [7]. However, severe defoliation for two consecutive years can promote mortality for up to 60–75% of trees in stands, depending tree size [5].

D. pini is a common forest pest in northern European coniferous forests, occasionally reaching outbreak levels. Outbreaks are eruptive, following several years of low population densities. Peak densities may typically continue for 1–3 years in one region until the population crashes [10]. *D. pini* consumes Scots pine stands of all ages, but prefers mature stands during the early phase of an outbreak [11]. Until the 1990's, outbreaks typically covered hundreds or thousands of hectares of pine-dominated forests in Finland [3, 10]. During the latest outbreak of *D. pini* in 1998-2001, approximately 500 000 hectares was defoliated, which is the most widespread insect outbreak ever recorded in Finland. The large scale of the outbreak area is common in Central but not northern Europe. *D. pini* is a late-season defoliator that feeds both on current and mature needles. This kind of feeding preference causes serious losses and makes *D. pini* a harmful forest pest and a tree-killer species [2].

Almost nothing is known about the total length of a recovery period after an outbreak by *D. pini*. Observations of the impact of defoliation on the rotation period of a stand have been published for some other forest pests, e.g. [12]. Consequences for forestry resulting from needle feeding by *D. pini* are still mostly unknown. The topics of interest of the present study are (i) to provide estimates of the reduced annual increment after defoliation by *D. pini*, (ii) to estimate tree mortality and (iii) to provide preliminary estimates of the economic impact of increment losses and tree mortality.

II. Materials and Methods

The study was carried out in SW Finland (Harjavalta 61°17' N, 22°09' E) in 1990-2002. The randomly selected mature trees were growing on a study site of 5.53 ha on dry sandy soil. Most of the Scots pines in the area were defoliated late in the season in 1989 by *D. pini*. The population crashed in 1990 after a single-year outbreak. Ten experimental groups consisted of three pines: the first pine tree had slight defoliation with approximately 10 % loss of needle biomass; the second tree had moderate defoliation with approximately 50 % loss of needle biomass; and the third tree had heavy defoliation with more than approximately 90 % loss of needle biomass. The distance between the trees was 2–5 m. The defoliation intensity was visually estimated in May 1990 from four different cardinal directions to an accuracy of 10 %. Increment cores were sampled for radial growth measurements in November 2000 in order to compare tree increment before and after defoliation. Only five trees in each defoliation category could be sampled due to earlier sampling

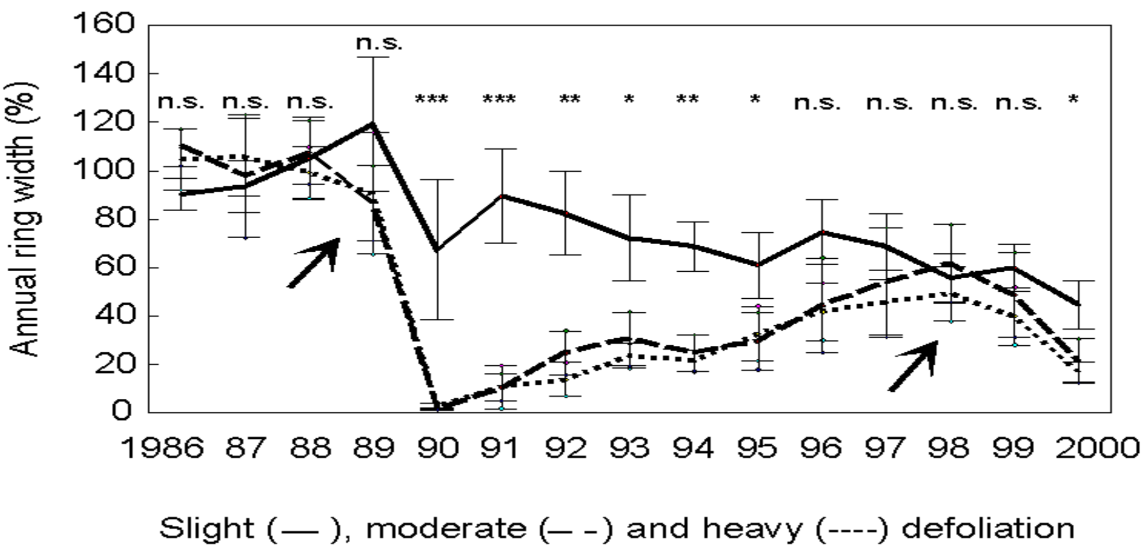

Fig. 1. Width of annual rings at breast height in Scots pines exposed to slight, moderate and heavy defoliation. Mean annual ring widths of years 1986-1989 were used for the baseline (100 %). Annual ring widths were compared to the mean annual ring width before the outbreak and the ratio expressed as a percentage (±s.e.) Asterisks indicate significant (ANOVA: P<0.001) differences between categories and arrows indicate the years of defoliation. In each defoliation category, n = 5. For defoliation categories, see text.

procedures. The width of annual rings was measured from the period of 1986-2000 (Fig. 1). The growth losses after defoliation caused by *D. pini* (i.e., from 1990 onward) were estimated on the basis of the width of annual rings in the four-year period prior to the defoliation year (i.e., 1986-1989). Means of ring widths for each defoliation category in that period represented a ring width of 100%. The widths of annual rings, following the outbreak year, were then compared with those means. When making these preliminary estimates, it was assumed that the reduction in radial increment and the reduction in volume increment were of the same order of magnitude.

Stand characteristics were measured in 2002 using a circular sample plot survey method with a changing radius, including at least 20 pines (Table 1). In each of five circular plots the diameter at breast height and height of all trees were measured. Trees were classified into three hierarchy positions: hold-overs, dominants and intermediates. For further information on the study site, see [4, 6].

TABLE I

Stand characteristics of the study site in Harjavalta. Standard deviations are shown in parenthesis.

Age (yr)	70.5 (6.9)
Trees ha^{-1}	1406 (727)
Mean diameter at breast height (cm)	15.81 (5.11)
Mean height (m)	11.62 (2.67)
Mean volume (m^3ha^{-1})	167.26 (67.56)

Tree mortality on a study site was estimated using a line plot survey method, where the width of each line was 10 m. Lines were situated horizontally across the site next to each other. The condition of trees was evaluated in 2002 and killed trees classified into three categories: hold-overs, dominants and intermediates. A similar classification was used in circular survey plots. Mean values for mortality calculations were adopted from those of circular survey plots. Tree mortality was nil in 1990 and most of the mortality had already happened by 1994 (P. Lyytikäinen-Saarenmaa, pers. observation).

Calculations of economic losses were based on the data of plot surveys and current timber prices of the province. Volume of the growing stock was calculated using the Smalian-Amgwerd formula ($v = 0.4d^2h$; where v = volume, d = diameter at breast height, and h = tree height) [13]. Diameters for earlier years were calculated by subtracting the corresponding mean ring widths needed from the diameters measured in 2000. The economic values were calculated using four variables: mean volume (m^3ha^{-1}) of Scots pine in three hierarchy categories, average annual volume increment, the intensity of pine sawfly defoliation, and value of timber. The mean volume of Scots pine in the study area was 167.23 m^3ha^{-1}, the estimated annual volume increment 5.4 m^3ha^{-1} [13] and the mean timber price €29/m^3.

One-way ANOVA was used to test the homogeneity of annual rings between means of defoliation categories prior to defoliation and the effect of defoliation on the width of annual rings, as well as tree mortality, between different hierarchy positions [14]. These tests were followed by Tukey's test for multiple comparisons.

III. Results

Prior to defoliation by *D. pini*, there were no statistically significant differences in annual ring widths between the defoliation categories in 1986 (F=1.22, df=2, *P*=N.S.), 1987 (F=0.08, df=2, *P*=N.S.), 1988 (F=0.10, df=2, *P*=N.S.) or 1989 (F=0.61, df=2, *P*=N.S.) (Fig.1). Ring widths differed significantly between defoliation categories in 1990–1995 and 2000. When comparing the annual rings with those of the four previous years, which did not vary from year to year (F=0.06, df=3, *P*=N.S.), the growth losses for the different categories in 1990 were 33%, 97% and 98 %, respectively (Fig. 1). The rate of annual growth for the categories was still 31%, 46% and 54% lower, respectively, eight years after the damage (Fig. 1). Growth responses, following the outbreak in 1989, were not possible to estimate after 1998, due to a new outbreak by *D. pini*. The rough estimate for the amount of a cumulative growth loss until 1998 was 33.11 m^3ha^{-1}.

According to our estimates of stand volume, the total cumulative amount of tree mortality was 3.46 m^3ha^{-1} (Table 2). Hold-overs represented most of the mortality (1.27 m^3ha^{-1}). There were no statistically significant differences in tree mortality between hierarchy categories (F=0.05, df=2, *P*=N.S.) Total tree mortality of the site after a single-year outbreak corresponded to 2.07% of the total volume of the growing stock per hectare.

Average economic values for growth losses in different defoliation categories and tree mortality were estimated for the year 1994, which represents an average year of the recovery period. We can assume that the total mortality happened before that year. Annual volume increment of the stand was estimated to be 5.4 m^3ha^{-1}. The average annual amount of growth loss after moderate defoliation was 4.06 m^3ha^{-1} and cumulative mortality 3.46 m^3ha^{-1}, totalling 7.52 m^3ha^{-1}. Therefore, an amount of annual growth losses can reach €118 ha^{-1} and cumulative mortality €100 ha^{-1} after a single year of moderate defoliation. Similarly, it is possible to estimate a value for average growth loss for each year during the recovery period. The estimated total economic loss for a nine-year recovery period, including cumulative growth loss and cumulative tree mortality, is €1060 ha^{-1}.

TABLE II

Tree mortality of the study site in Harjavalta. Hierarchy positions of trees are divided into three categories: hold-overs, dominants and intermediates. Standard deviations are shown in parenthesis.

Crown position	Mortality loss (m^3ha^{-1})
Hold-overs	1.27 (2.19)
Dominants	1.18 (0.38)
Intermediates	1.01 (0.54)
Total	3.46 (1.23)

IV. Discussion

Defoliation of Scots pine late in the season causes serious reductions in growth, occurring in the following year and later [7, 15]. Needle damage later in the season may produce different kinds of response in carbohydrate dynamics, depending on the needle age class consumed, crown fraction, and timing of defoliation [16, 2], resulting in high losses in radial, volume and height growth. Defoliation late in the season disturbs the most productive sources of carbohydrate, which is reflected in the subsequent stem growth [15]. Impact on radial and volume growth is approximately 2–3 times higher after late season defoliation, compared with early season defoliation [15, 9, 6]. It is evident that the amount of growth losses after needle damage are proportional to the intensity of feeding, as observed in several studies [7, 1, 2].

The present results are in accordance with the earlier findings on the amount of radial growth losses of Scots pine during the first recovery years [5]. Typically, several studies have failed to follow the total recovery period. Trees suffering from only slight defoliation approached normal growth rates after a year, showing the typical V –shaped decline-recovery pattern in radial growth [17]. Responses after moderate and heavy defoliation were almost identical, showing high losses during 7–8 years. Unfortunately, a new outbreak by *D. pini* started in 1998 and we lost the last part of the recovery period. It may take at least 10-15 years before the radial and volume growth is re-established after moderate or heavy defoliation [8, 9, 10]. Among late season feeders in Europe, *D. pini* seems to be one of the most disastrous defoliators on Scots pine.

Scots pine withstands even severe defoliation of one year quite well. Two or more years of continuous needle damage may cause substantial mortality [7], partly due to secondary stem-boring insects, such as bark beetles [5]. According to earlier observations, mortality rates are typically 4–24% in Europe [7,18]. Ref. [5] reported exceptionally high mortality (60–75%) after a two-year outbreak. The outbreak in Harjavalta area extended only a year, causing 2% mortality of the stand volume within the following 3-4 years. Mostly large trees suffered from mortality. This indicates the preference of *D. pini* for mature trees in this phase of an outbreak. The mortality pattern would have been different if the outbreak had continued for at least two consecutive years.

The rough estimates of economic consequences indicated a much higher impact of *D. pini* than revealed by the few earlier studies in Europe [3, 7, 18]. The feeding intensity by *D. pini* can quite often be moderate to heavy during peak densities of an outbreak, and the proportion of tree mortality can increase up to 70–80%, with considerable economic consequences. Losses in radial and volume growth mostly corresponded to the total economic loss after a single-year outbreak, but the figure would have been different after a longer-lasting outbreak. The length of a full recovery period still remains a partly open question, but the results of the present study indicate that the recovery period is long. Each of these “recovery” years will add annual increment losses to the total economic losses.

The present study carries some limitations and sources of error. First of all, there was only one study site, without real controls. There should have been several similar sites in different parts of the whole outbreak area, where similar treatments and sampling could have been carried out. Besides, a true experiment would have needed control sites on undefoliated, similar stands in the province. Control sites could have provided trends for normal annual increment. The results of this case study still accorded closely with the observations in other studies [7, 15, 5]. Secondly, information on other mortality factors is missing. There were some signs of pine shoot beetles in the study site, but obviously the population density of bark beetles was not high. Thirdly, the assumption was made that the decrease in radial and volume increment were of the same order of magnitude. Since our aim was to provide approximate, preliminary estimates, this generalisation seems justified. Finally, when calculating estimates of the economic consequences of the outbreak, some average parameters, e.g. annual increment of this kind of stand, were employed to represent the study site. Current mean timber price of the province was applied for the recovery period studied, not annual mean timber prices.

V. Summary and Conclusions

Annual increment losses mostly accounted for the total economic losses after a single-year outbreak by *D. pini*. Cumulative tree mortality was highest in hold-overs, and total mortality approximately equalled the level of annual volume increment of the stand. Growth losses were still considerable after a nine-year recovery period, particularly in trees with moderate and heavy defoliation. The present study gave results from a single forest area only. This area is characterised by dry soil and is impacted by nearby industries. A similar study on a geographically more dispersed area is needed to develop a more reliable and comprehensive estimate of the impact of defoliation on different kinds of stands. The future aim is to construct a model using site data like this, connected with data of the population dynamics of pine sawflies. This model would predict the trends of insect populations and defoliation intensity, determine risk thresholds on the basis of population prognoses, and estimate the economic consequences of the damage. The model would link methods of integrated pest management and sustainable forest management, providing a highly practical and important tool for forest managers.

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