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Recovery of crown transparency and stem growth of *Pinus sylvestris* after infestation by *Gremmeniella abietina*

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ABSTRACT

In Sweden, in the year 2000, an outbreak of the fungus *Gremmeniella abietina* (Lagerb.) Morelet resulted in varying severities of defoliation of mainly 30–50 year old Scots pine (*Pinus sylvestris* L.) stands. The main aims of this study were to investigate the recovery of the trees at permanent sample plots up to 13 years after the infestation, in terms of crown transparency (CT) and stem growth, as well as to draft recommendations for silvicultural practices in boreal Scots pine forests attacked by *G. abietina*. In the five infested stands monitored, the total mortality averaged 506 trees ha^{-1} (44%) and 8.9 m^2 ha^{-1} (37%). Most of the mortality occurred within two years of the attack. Over the final 8-year period, the mortality was at a similar level to the reference stands. Infested Scots pine trees, still living 13 years after the infestation, had recovered at this final assessment in terms of CT and showed similar CT levels as the trees in reference stands lacking obvious infestation. The stem growth of individual trees with a low initial CT (<40%) exhibited increased growth (i.e. an effect of reduced competition), in comparison to uninfested reference trees, over almost the whole 13-year monitoring period after the infestation. Growth reductions were detected for trees with an initial CT of >40%, and the reduction lasted 2–8 years, depending on the initial CT, after which the growth increased compared to reference trees. The most damaged small trees (CT > 80%, diameter < 12 cm) did not reach the reference tree growth level. In the infested stands, the proportion of pines with dead tops were higher and the diameter-height ratio increased, both significantly. Compared with the reference stands, the reductions in basal area and volume increment at the stand level in the infested stands were estimated to be 21–44% (n = 4) and 42–63% (43–74 m^3 ha^{-1}, n = 3), respectively, during the 13 growing seasons after the attacks. This reduction in basal area increment lasted for about a decade. From a silviculture stand management perspective, it is suggested that trees with a CT above 80% due to *G. abietina* infestation should be felled so that the remaining trees have a high probability of survival with stand growth being fully recovered after about a decade in terms of CT and stem growth. A sanitary cut should be undertaken as soon as possible after an infestation.

1. Introduction

The extensive outbreak of *Gremmeniella abietina* (Lagerb.) Morelet in Sweden at the beginning of this century infested large areas of Scots pine (*Pinus sylvestris* L.) forests (Wulff et al., 2006). At that time, there was limited knowledge of how to treat infested stands. From a silvicultural perspective, as discussed by Sikström et al. (2011, 2005), it is not obvious whether a *G. abietina* infested stand should be left untreated or whether a sanitary cut (thinning or clear cut) should be undertaken. Such a decision requires relevant knowledge of the probability of tree mortality, the recovery process of infested trees and the potential growth losses of the surviving trees.

It has been shown that *G. abietina*-induced crown transparency (CT) can cause the death of *Pinus* spp. trees (Senn, 1999) with a CT value >90% indicating a high probability of mortality for Scots pine (Sikström et al., 2011, 2005). In general, for coniferous species, irrespective of the cause of damage, a CT above 90–95% appears to be critical and is associated with a substantial increase in the probability of death for individual trees (cf. Cedervind, 2003; Cedervind and Långström, 2003).

Five years after a *G. abietina* attack, Sikström et al. (2011) reported a mean CT in the range of 59–73% in infested stands compared with 17–22% in unaffected reference stands. Långström et al. (2001) reported almost fully-recovered foliage of Scots pine seven years after a single year of total defoliation by *Diprion pini*, whereas

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after two consecutive years of total defoliation, needle biomass had only reached 50–70% of full biomass seven years after the second defoliation. Thus, recovery of the foliage of Scots pine trees may be a slow process, especially after severe defoliation.

The growth of Scots pine has also been shown to decline after infestation by *G. abietina*, and the reduction seems to increase with the severity of the infestation (Sikström et al., 2011; Riihinen and Uotila, 1992; Aalto-Kallonen and Kurkela, 1985). In the study by Sikström et al. (2011), the growth of the most defoliated trees (CT > 79%) had not started to recover five years after the *G. abietina* attack whereas the growth rate was more or less back to the reference level in trees with a CT of 40–79%. Moreover, unaffected trees and those with a low CT in an infested stand i.e. below c. 40%, retained or increased their growth, after a lag phase of two to three years, explained by reduced competition due to high mortality and the decline in heavily defoliated surrounding trees. After a five-year monitoring period, Sikström et al. (2011) estimated the stem volume growth reduction to be 53–73% on an area basis in the infested Scots pine stands where relevant comparison to a reference stand was possible (Sikström et al., 2011).

Heavy defoliation by insects has also been shown to cause considerable growth reduction in Scots pine stands (Långström et al., 2001; Straw, 1996; Austarå et al., 1987). Basal area increment (BAI) was reduced by approximately 30% over a five-year period following one year of total defoliation of Scots pine by *Diprion pini*; at the end of this period, growth had recovered fully (Långström et al., 2001). In the same study, BAI was reduced by 40–70% over a six-year period after two years of subsequent total defoliation, and the authors estimated that the period of reduced growth would last 7–8 years. After two consecutive years of heavy defoliation by *Neodiprion sertifer*, BAI was reduced by approximately 30% in Scots pine stands over a nine-year period, with the growth rate not returning to its original level by the end of the period (Austarå et al., 1987).

From a silvicultural stand management perspective, Sikström et al. (2011) suggested that sanitary thinning should be undertaken of Scots pine trees with a CT of 80% and higher, in order to provide a high survival probability for Scots pine trees after a *G. abietina* attack, as well as a safety margin against the risk of *T. piniperda* stem attacks. In the same study, Sikström et al. (2011) concluded that a five-year period was not long enough to estimate the complete growth response to a *G. abietina* attack of the actual magnitude in the investigated stands (see above).

At the end of 13 growing seasons after the initial attack, we revisited the permanent sample plots in both the infested Scots pine stands and the reference stands established by Sikström et al. (2011, 2005). The aims of this study were to: (i) record any further mortality after an infestation by *G. abietina*, (ii) investigate the recovery of the infested Scots pine trees in terms of tree crown transparency (CT) and stem growth, (iii) estimate the growth reduction in the infested stands over this period, and (iv) compile proportions of trees with dead tops and analyse changes of the diameter-height ratio (DH ratio) of individual trees. In addition, based on the gathered data, we attempted to draft recommendations for silvicultural practices in boreal Scots pine forests attacked by *G. abietina*.

2. Materials and methods

2.1. Sites, stands, sample plots and assessments

The study method consisted of comparing data from permanent sample plots (n = 5 or 10) in five Scots pine (*Pinus sylvestris* L.) stands infested by *G. abietina* ("Gremmeniella stands"; GREM11, 12, 21, 22 and 31) with data from plots (n = 5–7) in four reference stands (REF110, 210, 220 and 310). The reference stands had no obvious old or new *G. abietina* infestations. All stands were located in the southern central part of Sweden within a radius of about 60 km. The sites, stands and the establishment of plots are described in detail in Sikström et al. (2011, 2005).

In this study, the data recorded allowed comparisons of stem growth between GREM and REF stands over a period of 13 years after the *G. abietina* outbreak, and one (single year, 2013) comparison of CT. The stands compared were: GREM 11 and 12 vs. REF110, GREM21 vs. REF210, GREM22 vs. REF220 and GREM31 vs. REF 310. These comparisons were considered as "blocks" in the statistical analyses (see Section 2.3). However, since the analysis of growth data from stands GREM31 and REF310 indicated that fertilizer was applied in different years (cf. Sikström et al., 2011), the growth data from these stands were omitted from the analysis.

The procedures used for measuring tree properties (size, stem growth and CT) in all stands are described by Sikström et al. (2011, 2005). The same procedures, with some exceptions, were used for both GREM and REF stands. In all, 1153 Scots pine trees in the GREM stands and 621 Scots pine trees in the REF stands were monitored during the study.

The most recent assessments of CT in both GREM and REF stands were carried out in the spring of 2013 (27 May–5 June). The CT assessments were carried out by the same person on all occasions. It was done from the ground by using binoculars, and each tree's degree of CT was related to its full needle status, as imagined by the observer. The degree of CT was classified in percentages (0, 1, 2, ..., 100%) for the whole tree-crown. A tree having a CT of 100% was defined as dead (cf. Sikström et al., 2011, 2005). Data for CT are presented in 10% classes and means per stand, as well as tree mortality (CT = 100%). Furthermore, during all CT assessments (2002–2005 and 2013), the presence of a dead and/or new top was recorded. A dead top was confirmed when the top bud and/or the top leader was dead i.e. it was impossible to form a new top leader from the existing top bud in the following growing season. In many cases, within a few years, a living side-branch formed a new top to the tree if the original top had died.

The growth assessment was carried out in September 2013. All living trees at the time of assessment were cross-callipered (mm) at breast height, and increment cores (18 growth rings) were sampled. Tree ring widths in the cores were measured under a microscope (resolution 0.01 mm). The tree heights were re-measured (dm). In total, 645 Scots pine trees in the GREM stands and 604 Scots pine trees in the REF stands were included in the growth assessment.

2.2. Calculations

2.2.1. Tree mortality and crown transparency

Data for tree mortality are presented as number of trees ha^{-1} and basal areas (BA) ha^{-1} per stand for the different assessments.

Annual frequencies of CT (10% CT classes), for Scots pine trees still alive in 2013, were calculated for each stand, along with mean frequencies for all stands, as well as dead trees (%) of all trees per stand.

2.2.2. Tree-level growth

The stem growth of individual trees in the GREM stands was evaluated. The relative annual basal area increment of an individual tree (T-BAI_r) was calculated for the whole 13-year-period as:

$$\text{T-BAI}_r = \text{BAI}_i / \text{BAI}_b, \quad (1)$$

where BAI_i = basal area increment in year i during the investigated post-infestation 13-year period, and BAI_b = mean annual basal area increment of the pre-infestation period (years −5 to 0).