Article

Long-Term Effect of *Lophodermium* Needle Cast on The Growth of Scots Pine and Implications for Financial Outcomes

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Abstract: In Northern Europe, climate change may facilitate the prevalence of Scots pine, yet also promote the spread of pathogens attacking this species. A common biotic risk for Scots pine in nurseries and young stands is *Lophodermium* needle cast, primarily caused by *Lophodermium seditiosum*, which negatively affects the survival and growth of saplings. Reduced tree growth has been observed several years after damage by *Lophodermium* needle cast. However, for decision-making in protection or resistance breeding, an estimate of financial loss is important. Thus, the study aimed to assess the long-term influence of *Lophodermium* needle cast on the growth and financial value of Scots pine stands. The effect of needle cast damage during the sixth growing season on growth at the age of 17 years was evaluated in a control-crossed Scots pine progeny trial, and the results indicated a significantly negative effect on the height and diameter of the trees. A significant family effect also existed on the severity of the needle cast damage. Long-term simulations indicated that severely damaged Scots pines had a reduced equivalent annual annuity (EAA) of almost 100% at the final harvest. More intensive early management to reduce stand density could partly compensate for losses caused by needle cast. A higher EAA for the most resistant group of trees regardless of the stand management scenarios suggests an economically justified potential for improved resistance. Strong negative (−0.62 to −0.70) correlations of height and survival with the proportion of severely affected trees at the family mean level implies that resistant genotypes can be selected along with improved growth in progeny trials, which are affected by needle cast.

Keywords: tree resistance; Scots pine pathogens; biotic risks; financial analysis; equal annual annuity; tree breeding

1. Introduction

In the hemiboreal regions of Europe, climate change can lead to an increased share of Scots pine (*Pinus sylvestris* L.), substituting for other tree species, such as Norway spruce *Picea abies* (L.) H. Karst. [1]. Nevertheless, *Pinus* spp. also have potential risks. They are more susceptible to needle cast and needle blight than other conifers [2,3]. Climate change has a direct influence on both trees and pathogens, and the interactions between them, resulting in changed disease effects and more frequent and severe attacks [4–8]. Since the 1990s, several severe outbreaks of *Lophodermium* needle cast caused by *Lophodermium seditiosum* in the Baltic region, Poland, and Fennoscandia have occurred, and it is still one of the most common needle diseases of pines [9–14].

Lophodermium is a complex fungal genus consisting of both needle endophytes and pathogens. The pathogenicity of *L. seditiosum* has been demonstrated in vivo [15], and it causes needle loss of young pines in nurseries and forest stands [3,11,16]. Trees retain needles for several years; however,

older needles are less photosynthetically active than younger ones [17]. Thus, a current year needle infection leads to reduced growth (annual increment) and survival [18]. Moreover, biotic disturbances may interact with each other [19], and the damage to forest stands could be the result of a complex of infections. For instance, the outbreak of *L. seditiosum* in Estonia coincided with the serious spread of *Dothistroma septosporum* [7,12]. The severity of Lophodermium needle cast damage decreases with age, and trees older than 10 years are rarely infected [3]. Nevertheless, growth reduction related to the defoliation caused by Lophodermium needle cast can last several years after the attack [20].

The trees' genetic response and adaptability to new climate conditions are slower than those of the pathogens [6,21]. As a result, pathogens can increasingly reduce the monetary value of forests. Therefore, management practice might be reconsidered and altered to mitigate the effect of pathogens on forest stands [22]. Although disease by itself ensures natural selection [23] and fungicides may be an effective method of preventing forest diseases in nurseries [6,16,24], resistance against fungal pathogens could be included in breeding programmes [6,25–29], thus preventing severe damage and providing improved yield and stem quality. Genetic effects on the resistance to *Lophodermium* needle cast have been indicated [3,30–33].

Information on the longer-term effects of Lophodermium needle cast is important to project timber and financial losses across the rotation period and evaluate alternative management scenarios to mitigate risks. Nevertheless, most studies in European forests have focused on natural disturbances, such as wind, fire, and (to some extent) pests, while the effects of pathogens have been relatively little studied [34–39]. In addition, economic analysis of natural forest disturbances to a large extent had focused on wildfires [19] but the long-term effects of fungal pathogens, including Lophodermium needle cast, on forest management profitability have been sparsely analysed. Therefore, the aim of this study, based on the progeny trial information, is to assess the long-term influence of Lophodermium needle cast on the growth and financial value of Scots pine stands.

2. Materials and Methods

2.1. Study Material

The study was conducted in a Scots pine control crossing progeny trial established in the eastern part of Latvia near Kalsnava (56°40' N, 25°57' E). The control crosses were done using 10 clones of local (Latvian) origin. In total, 98 full-sib families were obtained and represented in the trial. The trial was established on rather poor, sandy soil corresponding to the *Vacciniosa* forest type [40], and the trees were planted in four replicates of 15-tree-block-plots for each family with a planting density of 5000 trees ha⁻¹ (spacing 2 × 1 m). In total, 4154 initial planting spots were available for analysis, since some families were not present in all four replications and some plots were excluded from analysis due to low initial survival shortly after planting.

In the trial, needle cast infestation may have originated from the surrounding mature and young Scots pine stands. Needle cast symptoms caused by *Lophodermium* spp. were identified by a single observer using the macroscopic features of the fungus [15]. The damage was assessed in June of the sixth growing season by visually evaluating a proportion of the needles on the last height increment, which was infected at the end of the previous growing season and thus turned yellow then brown during the given season (at the time of the assessment). The needle cast damage assessment was done on a five-grade scale typically used in local nurseries and progeny trials according to the proportion of damaged needles: Grade 1 corresponds to 0% to 5%, Grade 2 to 6% to 35%, Grade 3 to 36% to 65%, Grade 4 to 66% to 95%, and Grade 5 to 96% to 100% of the damaged needles. For the analysis of the family mean level, the proportion of severely damaged trees was used, corresponding to the pooled proportion of the trees in Grades 4 and 5. The tree height (± 0.01 m) and diameter of the root collar (± 0.001 m) at the age of 5 years, and the tree height (± 0.1 m) and stem diameter at breast height (DBH ± 0.001 m) at the age of 17 years were measured.

2.2. Statistical Analysis

The Chi-square test was used to assess the differences in the distribution of the damage grades between trees that died at the age of 6–17 years and trees that survived until the age of 17 years. Considering the experimental design, the family effect on the damage grade was assessed using a generalised linear mixed-effect model applying the Poisson distribution:

$$y_{ijkl} = \mu + F_i + r_j + p_k + \varepsilon_{ijkl}, \quad (1)$$

where y_{ijkl} is the response variable (damage grade) of the l th tree from the i th family in the k th multiple-tree plot nested within the j th replication, μ is the overall mean, F_i is the fixed effect of the i th family, r_j is the random effect of the j th replication, p_k is the random effect of the k th plot, and ε_{ijkl} is the residual error.

At the individual tree level, the effect of the family and damage grade at the time of the first height measurements on the tree height and diameter at the repeated height measurements was assessed with a linear mixed-effect model, using the tree height or diameter at the first measurement as a covariate:

$$y_{ijklm} = \mu + M_{ijklm} + D_i + F_j + M_{ijklm}D_i + M_{ijklm}F_j + D_iF_j + r_k + p_l + \varepsilon_{ijklm}, \quad (2)$$

where y_{ijklm} is the response variable (height or diameter at the age of 17 years) of the m th tree with the i th needle cast damage grade from the j th family in the l th multiple-tree plot nested within the k th replication, M_{ijklm} is the fixed effect of the initial measurement at the age of 5 years, D_i is the fixed effect of the i th damage grade, F_j is the fixed effect of j th family, $M_{ijklm}D_i$ is the interaction of the first measurement and damage grade, $M_{ijklm}F_j$ is the interaction of the first measurement and family, D_iF_j is the interaction of damage grade and family, r_k is the random effect of the k th replication, p_l is the random effect of the l th plot, and ε_{ijklm} is the residual error. Pearson's correlation was used to assess relations between traits (tree height and diameter, proportion of severely damaged trees, and survival) at the family mean level. All tests were performed and all data analyses were conducted in R (v. 3.6.1) with 95% confidence interval ($\alpha = 0.05$) [41].

2.3. Evaluation of the Financial Outcome

The financial value at the final harvest was estimated from five-year period simulations in which the tree dimensions at a certain age were obtained using the local growth models (Supplement 1) [42]. Regarding the small number of trees corresponding to grades 1 and 5, simulations were done for each of three pooled damage grade groups (grade 1 to 2, grade 3, and grade 4 to 5), using group mean values of height, DBH, number of trees, and basal area at the age of 17 years as input data. No modifications in models were applied for different damage grades.

In simulations, three stand densities at the age of 17 years were used as input: the actual density (1930 to 3900 trees ha^{-1}), 1400 (intensive management regime), and 2500 (conventional management regime) tallest trees ha^{-1} . For each damage grade group, three different commercial thinning regimes were applied in the simulations: (i) thinning done when the relative stand density reaches 0.95 and is reduced to 0.7, (ii) thinning done when the relative stand density reaches 0.95 and is reduced to 0.60, and (iii) no thinning applied (Table S1). The analysis was applied for two final harvest scenarios: (i) when the cutting age (101 years) or (ii) target diameter (≥ 35 cm) was reached according to the current legislation in Latvia.

The volume of the logs was determined from the tree assortments in the stand according to the local equation [43]. Income from the harvest was calculated from the volume and prices (Central Statistical Bureau of Latvia 2018) of the assortments (Tables S2 and S3) [44]. To reflect the sensitivity to the situation in the timber market, income was estimated for three price levels—average, minimum, and maximum price (Table S3).

The financial value of the stands was calculated using the equivalent annual annuity (EAA) with 2%, 3%, and 4% interest rates [45]:

$$EAA = \frac{r * \sum_{t=1}^n \frac{R_t}{(1+r)^{n*5}}}{1-(1+r)^{-n*5}}, \quad (3)$$

where r is the interest rate (%), R_t is the net cash inflow-outflow during a single period t (EUR), and n is the number of five-year periods. Differences in EAA among groups with various damage grades were estimated using the analysis of variance and post-hoc Tukey's test.

3. Results

In the study trial, the survival of trees was 81% (3373 out of 4154) at the age of five years, and 54% at the age of 17 years. In the sixth growing season, 52% of trees had the damage grade 4 and 5 (>66% damaged needles). The proportion of trees in the damage grades differed significantly ($p < 0.01$) between trees that survived until the age of 17 years and trees that died at the age of 6 to 17 years (Figure 1). By the age of 17 years, more severely defoliated trees had died than less damaged trees.

Figure 1. Tree distribution among the needle cast damage grades (1–5) for trees that survived until the age of 17 years and trees that died at the age of 6 to 17 years.

3.1. Needle Cast Effect on Scots Pine Growth

At the age of five years, the mean values $\pm$ 95% confidence intervals of the tree height and diameter at the root collar were 130 ± 1.0 cm and 25 ± 0.2 mm, respectively. At the age of 17 years, corresponding values of tree height and DBH were 8 ± 0.1 m and 9 ± 0.1 cm, respectively. The tree dimensions among the damage grades differed significantly, with less-damaged trees being significantly ($p < 0.05$) higher than more-damaged trees (Figure 2).

At the individual tree level, the height at the age of 17 years was affected by the height at the age of five years, damage grade, and family (all $p < 0.01$). There was also a statistically significant interaction between the height at the age of five years and the family ($p = 0.02$). For DBH at the age of 17 years, the root-collar diameter at the age of five years and the damage grade were the only significant factors ($p < 0.01$). Trees less damaged by needle cast in the sixth growing season were higher at the age of 17 years. Trees that were initially (at the age of five years) high but less resistant to damage were shorter after 12 years than trees that were initially shorter but resistant to damage. A more pronounced decrease in the number of trees was found for initially shorter trees that simultaneously had a higher damage grade. Initially shorter trees included a lower proportion of undamaged trees.

Figure 2. Tree height at the age of five years (H5), height increment between the age of 5 and 17 years (Delta_H), and mortality (%) between the age of 5 and 17 years. Whiskers denote 95% confidence interval.

The full-sib family had a statistically significant effect on the damage grade ($p < 0.01$). At the family mean level, the relation between the proportion of severely damaged trees and growth traits (height and diameter at both ages) was negative (Table 1, Figure 3; $p < 0.05$; $r = -0.25$ to -0.62). No relation was found between the proportion of damaged trees and survival at the age of five years (i.e., until the assessment of the needle cast damage), yet the relation between the proportion of severely damaged trees and the survival at the age of 6 to 17 years was strong and negative (Table 1; $r = -0.70$, $p < 0.001$).

Table 1. Survival, tree dimensions, and correlation coefficients between these traits and the proportion of severely damaged trees (pooled grades 4 and 5) at the family mean level.

Trait	Correlation Coefficient with the Proportion of Severely Damaged Trees ¹	Range of Family Mean Values ($\pm$ 95% Confidence Interval)	
		Minimum	Maximum
Survival at the age of 5 years (%)	−0.07	43	100
Survival at the age of 17 years relative to that at age 5 (%)	−0.70 ***	6	96
Height at the age of 5 years (cm)	−0.25 *	103 $\pm$ 10.1	157 $\pm$ 13.4
Diameter of the root collar at the age of 5 years (mm)	−0.37 ***	20 $\pm$ 1.8	32 $\pm$ 2.2
Height at the age of 17 years (m)	−0.62 ***	6 $\pm$ 1.3	10 $\pm$ 0.5
Stem diameter at the breast height at the age of 17 years (cm)	−0.40 ***	7 $\pm$ 1.3	12 $\pm$ 2.9

¹ Proportion of trees evaluated as grades 4 and 5 relative to the number of trees at the age of five years; * $p < 0.05$, *** $p < 0.001$.

Figure 3. The relation between tree height at the age of 17 years (H17) and proportion of severely damaged (pooled grades 4 and 5) trees in the sixth growing season (P6) at the family mean level (families ordered descending according to mean height). Whiskers denote 95% confidence intervals.

3.2. Long-Term Effects on Financial Value

Simulation results indicated a significant ($p < 0.01$) effect of needle cast damage on EAA. At both the target age (101 years) and target DBH (≥ 35 cm), the seriously damaged (grades 4 to 5) group of Scots pine had a significantly lower EAA than the group of undamaged or slightly damaged (grades 1 to 2) trees, regardless of the density at the age of 17 years, commercial thinning regime, or price level (Figure 4, Table S4). For all damage levels, EAA at the final harvest according to the target DBH was more than double compared to the target age of 101 years. The target DBH for grades 1 to 2, 3, and 4 to 5 were reached on average at the age of 64, 77, and 97 years, respectively. The mean EAA reached 62.3 ± 18.7 EUR ha⁻¹ for damage grades 1 to 2 at the final harvest time according to the target DBH, whereas it was lowest (0.8 ± 9.4 EUR ha⁻¹) for trees with grades 4 to 5 at the conventional final harvest time (Figure 4).

Figure 4. Average equal annual annuity (EAA, EUR ha⁻¹) applying 2%, 3% and 4% interest rates for different needle cast damage groups at two final harvest scenarios: cutting according to target age (101 years) or when the minimum allowable diameter at breast height (DBH) is greater than or equal to 35 cm. Whiskers denote 95% confidence intervals.

In all simulated scenarios, the EAA reached the peak at the age of 35 to 45, tending to culminate earlier for groups with less needle cast damage and lower stand density at the age of 17 years (Figure 5). Regarding different commercial thinning regimes, the highest EAA for all groups was reached by applying a moderate commercial thinning regime, when relative density is reduced from 0.95 to 0.70 (Table S4). When applying a rate of 4%, the calculations for all price levels showed a similar tendency of EAA dynamics. The highest EAA during the simulated period was for the least damaged trees (grades 1 to 2) with a density of 1400 trees ha^{-1} at the age of 17 years, whereas the lowest EAA was estimated for seriously damaged trees in the actual density scenario (1930 trees ha^{-1}), reaching positive values only at the maximum price level. For all needle cast damage levels, EAA was lower for the higher initial density at the age of 17 years compared to the intensive early management scenario (Table S4). Nevertheless, all scenarios applying a rate of 4% had a negative EAA at the minimum price level, whereas the scenarios with lower density at the age of 17 years for groups with grades 1 to 3 showed a stable tendency to maintain positive EAA during the simulation period for the average and maximum price levels.

Figure 5. Equivalent annual annuity (EAA) dynamics with an interest rate of 4% for different initial densities (1400 trees ha^{-1} and actual density at the age of 17 years) and damage grades applying thinning regime 1 (reducing relative stand density from 0.95 to 0.70). Simulated scenarios: 1_2_1400: damage grades 1 to 2 with a density of 1400 trees ha^{-1} ; 1_2_3900: damage grades 1 to 2 with a density of 3900 trees ha^{-1} ; 3_1400: damage grade 3 with a density of 1400 trees ha^{-1} ; 3_3000: damage grade 3 with a density of 3000 trees ha^{-1} ; 4_5_1400: damage grades 4 to 5 with a density of 1400 trees ha^{-1} , and 4_5_1930: damage grades 4 to 5 with a density of 1930 trees ha^{-1} .

4. Discussion

Severe defoliation due to *L. seditiosum* infection is a common type of damage that affects Scots pine in nurseries and young stands in the Baltic sea region [11,18,20,23,31,46]. In our study trial, more than half of the trees were severely damaged by Lophodermium needle cast in the sixth growing season, yet damage had likely occurred for several years. The magnitude of the damage may vary substantially among locations [31], due to the irregularity and high dependence on climatic factors [47]. An Estonian study concluded that the total precipitation from May to August of at least 300 mm

indicated a potential epidemic the next year [20]. Induced by the changing climate, milder winters are also reported as a causal factor for increased needle cast damage [11]. Overall, the risks of fungal pathogens, such as *L. seditiosum*, are increasing with environmental changes towards higher humidity and temperatures [48].

We observed a significantly different proportion of trees in the different damage grades for individuals that survived and died at the age of 6 to 17 years, with the latter group being more affected by *L. seditiosum* (Figure 1). A four-times higher mortality rate between the age of 5 and 17 years for a group of severely damaged than minorly damaged trees (ca. 20% and 80%, respectively) indicated a substantial negative impact on survival (Figure 2). Although the loss of dead needles could not necessarily be a direct cause of death for the infected tree, seedlings had reduced viability and weakened new shoots [13,15], thus becoming more susceptible to other abiotic and biotic risks [18]. Needle cast damage is also reported to negatively affect survival in open-pollinated progeny trials, where the mortality of severely damaged trees reached 85% at the age of 12 years [18].

Loss of actively assimilating foliage and nutrients in the shedding needles reduces tree growth [49]. Our results indicated significant differences in height and DBH among trees with different needle cast damage severity, with less-damaged trees having a clear tendency to become larger at both individual and family mean level (Figure 2 and Table 1). Both height and DBH at the age of 17 years depended on the initial height at the age of five years; however, the resistance to needle cast seemed to have a stronger effect. As a result, the growth of initially smaller but more-resistant trees after 12 years surpassed the dimensions of the trees that were initially larger but less resistant. The height of Scots pine saplings at the age of 12 years was reported to be negatively affected by cumulative needle cast damage during the fourth to sixth growing seasons [18]. The three youngest needle sets reported to have a significant influence on the current year's height and radial increment [49]. For 3- to 11-year-old Scots pines, a decrease in the height and radial growth had been observed to reach 7% to 18% during the epidemic year and the three subsequent seasons, compared to the long-term average [20].

The effect of damage by forest pathogens on full-rotation profitability can be comparable to or even exceed wind damage effects [50,51], for which various risk scenarios in boreal forests have projected up to a 13% lower net present value (NPV) compared to the optimised scenarios aiming for maximised NPV and minimised wind risk [39]. Similar to wind damage, the effect of pathogens, such as *L. seditiosum*, is a natural disturbance that alters the flow of forest goods, thus forcing management to adapt to mitigate the economic risks [19,22]. Regardless of management regime, EAA in our simulations tended to decrease with increasing damage severity (Figures 4 and 5, Table S4). Nevertheless, simulations assumed no further growth increment reduction after the age of 17 years and thus did not account for the possible slower future growth of the severely damaged group. Since *Lophodermium* damage may have a longer negative impact on growth up to the age of 30 years [20,52], the differences in full rotation productivity and profitability might be even higher. However, the negative effect of the reduced growth due to pathogen attacks even at an early age might have a long-term effect on other stand parameters and the monetary value of the final stand. On average, the estimated EAA from ca. 60 EUR ha⁻¹ year⁻¹ for the group with grades 1 to 2 was reduced by 100% to almost zero for severely damaged trees (grade 4 to 5) (Figure 4). For the Douglas fir, *Pseudotsuga menziesii* (Mirb.) Franco in New Zealand, the estimated cumulative reduction in the mean top height, basal area, and stem volume until a stabilized growth rate 14 to 20 years after Swiss needle cast effects (caused by *Phaeocryptopus gaeumannii*) was reported to reach 25%, 27%, and 32%, respectively [53]. For loblolly pine, *Pinus taeda* L., and slash pine, *Pinus elliottii* Engelm., the planting stock resistant to fusiform rust (*Cronartium quercuum*) was estimated to have an increased land expectation value ($r = 6\%$) by 40.2% to 89.8% and 6.1% to 40.3%, respectively, compared to susceptible stands, due to higher volume production [54]. In New Zealand, ca. 50% defoliation of radiata pine *Pinus radiata* D. Don at an early age reduced the net present value by 46% when applying a rate of 6% [55].

In contrast to wind and fire damage, which are generally followed by salvage logging of dead trees and a desirable shortened rotation, the most appropriate strategy to maximise profitability for

stands with reduced growth (without massive mortality) after defoliation by needle cast might be an increased rotation length aiming to reach a larger DBH and, hence, a higher stumpage value [22,56]. Our results indicated such a tendency for *L. seditiosum* damage, since EAA tended to culminate later with increasing needle cast severity (Figure 5). Nevertheless, for all damage levels, the highest EAA was reached earlier than the conventional final harvest age (101 years) when reaching the minimum allowable DBH (on average, at the age of 64 to 97 years; Figure 4).

Thinning is an important tool to reduce financial losses [56]. In our study, simulations with the input density (age 17 years) thinned to 1400 trees ha⁻¹ exhibited a higher EAA for even the most severely damaged trees compared to higher density scenarios (Figure 5, Table S4). Although profitability by applying more intensive management in young stand for severely damaged groups could not reach the same levels as a group of resistant trees, early thinning was effective to partly compensate for the reduced growth caused by defoliation [56]. However, following commercial thinnings with moderate intensity (reducing relative stand density from 0.95 to 0.70) resulted in a higher EAA than more intensive interaction, reducing relative stand density from 0.95 to 0.60 (Table S4). It is supported by other studies that heavy thinning reduces annual volume increment and hence total yield [57,58].

Overall, silvicultural measures, such as thinning, mitigate the financial consequences of needle cast epidemics; yet, control of this fungal infection is challenging [13]. One possible measure could be breeding for a more-resistant Scots pine. For instance, considerable improvement in the resistance of *P. radiata* to *Cyclaneusma* needle cast caused by *Cyclaneusma minus* has been achieved by culling susceptible genotypes when selecting for productivity [27]. Due to breeding activities in the southern USA, the reduction of fusiform rust in the slash pine from 50% to 36% has been achieved along with a genetic gain of 25% to 30% in forest productivity [59]. In addition, further selection for resistance to fusiform rust is estimated to reduce the optimal harvest age by ca. 20% [60]. For the radiata pine, the selection for reduced defoliation caused by *Dothistroma* needle blight is estimated to have a similar effect on profitability as the increased growth on pathogen-free sites [55]. The results indicated a significant genetic effect on *Lophodermium* needle cast resistance and, hence, the possibility to select and test potentially more-resistant genotypes. It was supported by strong negative correlations ($r = -0.62, -0.70, p < 0.01$) between survival and height at the age of 17 years and the proportion of severely damaged trees (Table 1) at the family mean level. Significant effects of provenance and genetic entries on resistance have been reported in earlier studies [18,30–32,47]. The results indicated that, if the risk of needle cast damage could be minimised by applying such measures as the selection of more resistant genotypes, the EAA financial outcome might be improved regardless of the decisions concerning a desirable management regime and final harvest time. Thus, we suggest further analyses of the potential breeding for improved *Lophodermium* needle cast resistance. Considering the earlier findings and the negative family mean correlations between needle cast damage and growth (Table 1, Figure 4), higher weights in the selection process could be allocated to the results of progeny trials with observed needle cast damage because height growth of superior families would already likely reflect resistance to the pathogen.

5. Conclusions

Lophodermium needle cast negatively affects both tree height and DBH 11 years after a pathogen attack. In long-term simulations, *L. seditiosum* attacks at an early age had a substantial effect on EAA at the final harvest, which was by an average of 61.5 EUR ha⁻¹ or 100% lower for severely damaged trees compared to the unaffected trees, applying a 2%, 3%, and 4% interest rate. Later EAA culmination for more damaged trees suggested a longer rotation time for more affected stands. However, more intensive early thinning may partly compensate for the reduction in growth and reduce the final harvest age, hence improving the financial outcome of already-affected stands. As indicated by the significant genetic effect on needle cast damage, the selection of more-resistant genotypes could potentially be included in Scots pine breeding activities.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/11/7/718/s1>, Supplement 1: Applied growth modelling system, Table S1: Commercial thinning schedule (removed volume, $\text{m}^3 \text{ha}^{-1}$) in simulated stands with different initial densities and thinning criteria, Table S2: Forest management operations and their costs used in the simulations, Table S3: Assortment prices at different price levels, Table S4: Equal annual annuity (EAA) for different Lophodermium needle cast damage levels in simulated management scenarios of various initial density at the age of 17 years, and different thinning regimes applied.

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