Original Research

Pine Sawfly (*Diprion pini* L.) – Related Changes in Scots Pine Crown Defoliation and Possibilities of Recovery

A. Augustaitis*

Lithuanian University of Agriculture, Forest Monitoring Laboratory, Studentų 13, LT-53362 Kaunas, Lithuania

Received: April 19, 2006
Accepted: November 30, 2006

Abstract

Recently, outbreaks of pine sawfly (*Diprion pini* [L.]) became one of the most relevant stresses resulting in widespread deterioration of Scots pine (*Pinus sylvestris* [L.]) conditions in Central and Northern Europe. At the beginning of the 1990s Lithuania experienced the largest outbreak of *Diprion pini L*. Field studies were carried out in middle-aged pine stands, exhibiting different degrees of damage caused by pine sawfly, in order to examine the resultant changes in Scots pine defoliation and death probability. "Mirror effect" in defoliation changes from tree decline to recovery was detected. If in the period of pest outbreak the largest pine trees, crown condition of which had been better than that of the other, suffered the most serious needle losses, then in the period of recovery these trees recovered most intensively. Intensity of tree mortality was in relation to stands mean defoliation degree. However, the relative diameter of dead trees did not differ among stands significantly (p>0.05) as suppressed trees died first. No threshold for crown defoliation, exceedance of which would inevitably result in Scots pine tree death, was found.

Keywords: *Diprion pini*, crown defoliation, crown recovery, tree mortality

Introduction

Recently considerable attention has been paid to the study of natural stresses contributing to changes in forest conditions. There is evidence to suggest that forest condition deterioration on a regional scale in Europe must not be confined to the stress of regional pollution alone [1], but to climatic stresses as well [2-4]. In the last decade the impacts of air temperature and precipitation have been shown to be extremely harmful as they can trigger a decline in forest conditions and predispose outbreaks of forest pests [5, 6] through the effects on physiological process of the insects, and their host trees [7].

Currently outbreaks of common pine sawfly (Diprionidae) have to be regarded as a significant threat to pine forests, not only because of the increase in affected areas, but also because of their high damage potential [8]. Much has been written about pine sawfly effect on tree growth and individual tree mortality. However, almost nothing is known about the total length of a recovery period of pine trees [9].

At the beginning of the 1990s Lithuania experienced the largest outbreak of *Diprion pini L.* in Scots pine stands located at well drained and infertile sites (*Pinetum cladoniosum* forest type) in the south of the country. This event offered an opportunity to analyze the suffered needle losses of trees from different diameter groups and crown condition classes over the damage period from 1991 to 1995, and their crown recovery intensity over the recovery period from 1996 to 1999, when pine sawfly population had declined to non-out-

*e-mail: algirdas.augustaitis@lzuu.lt

break density. The aim of the present study was to detect tree response to suffered needle losses caused by sawflies and revise planning of the forest treatments in damaged areas. The following research was carried out:

- an analysis of the increase in crown defoliation over the period of pest attacks;
- an analysis of tree crown recovery when population of forest pests declined to non-outbreak density;
- an analysis of tree mortality;
- an analysis of the threshold of tree crown defoliation to cause mortality.

These analyses allowed advancing our knowledge on recovery process, death probability of damaged trees, and tree response to foliage losses, *i.e.* threshold of defoliation level, above which trees should inevitably die. Deeper knowledge should help in choosing forest treatments in sawfly-damaged pine stands.

Method and Material

The study was performed in Dzukija National Park (NP) located in the southern part of Lithuania. In 1991, in order to monitor pine conditions, 15 permanent observation stands (POS) were selected according to methodology with a three-stage sampling pattern:

(1) sampling of research stands;
(2) sampling of the circular plots within each research stand;
(3) sampling of the trees for more detailed measurements of the tree crown parameters and tree ring analysis (the latter data were left out from the analyses).

Each pine stand included twelve circular sample plots with an average of 15-20 trees. The sample plots were distributed in a systematic way – according to a grid. 170-220 sample trees in each POS represented all social classes, *i.e.* from hold-overs and dominant to suppressed trees. This tree number enabled an estimation of the relationship between relative tree diameter and crown defoliation or tree mortality. Relative tree diameter was computed comparing diameter of sample trees with mean diameter of a stand and classified in 0.2 step groups (from 0.4 to 1.6).

When the pine sawfly (*Diprion pini* [L.]) outbreak occurred, middle-aged (51-80 years) pine stands were damaged most intensively. Therefore, 8 POS from this maturity group were selected from the net of the sampling stands. These stands were classified into 3 groups (Table 1) according to the level of mean defoliation (intensity of the suffered needle losses) for the year 1995 and investigated in detail. From 1993 to 1999 crown defoliation of all sample trees in these POS was assessed annually in August employing ICP Forest monitoring methodology in 5% steps (10). According to the defoliation level 5 tree condition classes were distinguished: class 0 (undamaged trees) – defoliation up to 10%; class 1 (slightly damaged trees) – defoliation 15–25%; class 2 (moderately damaged trees) – defoliation 30–60%; class 3 (severely damaged trees) – defoliation 65–95%; class 4 (100%) – dead trees.

Fisher test was employed to estimate the significance of differences in crown defoliation changes among different tree condition classes and relative diameter groups over the periods of damage and recovery.

Table 1. Main parameters of the considered Scots pine stands.

POS	Stand dendrometric parameters						Mean defoliation			Dead trees	
	Age	Mean diameter	Mean height	Basal area	Volume	Tree density	1991	1995	1999	1991-1995	1996-1999
	year	cm	m	m^2/ha	m^3/ha	unit/ha	%	%	%	%	%
Slightly damaged stands											
1-02	70	29.9	20.9	31.0	307.8	442	20.8±0.9	35.8±1.3	25.8±1.3	1.3	1.9
2-07	60	27.5	18.2	23.2	209.4	392	21.1±1.2	37.8±1.1	23.2±1.0	2.1	0.0
3-15	80	30.4	21.0	30.4	312.9	418	21.6±1.3	34.2±1.3	27.4±1.7	3.2	6.0
Moderately damaged stands											
4-01	60	23.0	18.5	23.2	211.9	560	25.9±1.5	43.8±1.4	29.4±1.6	3.2	1.7
5-08	70	29.8	20.5	24.8	245.7	355	21.2±1.2	42.5±1.2	24.4±1.1	5.2	2.0
6-14	70	26.7	19.4	25.8	255.6	461	23.6±1.1	44.0±1.0	25.9±1.1	1.5	2.7
Severely damaged stands											
7-03	50	17.3	17.4	27.2	246.4	1156	23.0±1.1	59.0±1.2	34.9±1.7	6.8	11.2
7-05	70	26.1	17.3	22.2	200.8	413	28.8±1.7	54.6±1.3	31.7±1.9	4.5	17.9

Results

Outbreak of *Diprion pini* started in 1992 after very hot and dry vegetation period in 1991. The highest level of tree crown defoliation was observed in the third year of the outbreak, in 1994. In the subsequent year mean crown defoliation in slightly damaged stands increased significantly (by approximately 3%), in moderately damaged stands remained at the same level, whereas in severely damaged stands significant decrease in mean defoliation (by 8%) was recorded (Fig. 1).

In 1996 biological insecticide Foray-48B was applied to suppress sawfly populations and gradual recovery of tree crown condition started. Until 1999 pine defoliation in severely damaged stands decreased from 65 to 34%, in moderately and slightly damaged stands – from 43% to 26% and from 36% to 25%, respectively.

Increase in Tree Crown Defoliation Over the Period of Pest Attacks

F-test statistics indicated that in the group of severely damaged stands differences in suffered needle losses among trees from different condition classes and relative diameter groups were most statistically significant ($p<0.000$) (Table 2). The greater the tree diameter, the more intensive the increase in tree crown defoliation (Fig. 2.). Defoliation of the suppressed trees (Dr= 0.4-0.6) increased by 30% (from 60% to 90%, *i.e.*, about 1.5 times), whereas of the hold-overs (Dr > 1.4) – by more than 50% (from 15% to 65%, *i.e.*, more than fourfold).

The trees that had not been damaged before the sawfly outbreak, suffered the most serious needle losses (Fig. 2). Crown defoliation of these trees increased by 50% or more than 5 times. Suffered needle losses of the trees that had already been slightly and moderately damaged due to the effect of other stresses were lower and made approximately 45% and 35% or crown defoliation of these

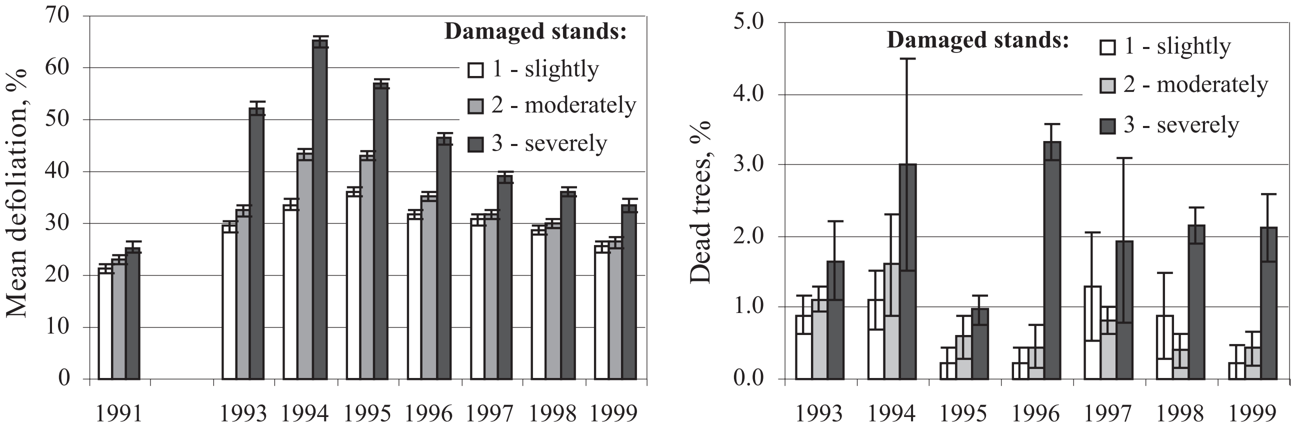

Fig. 1. Changes in mean tree defoliation and annual mortality with standard errors in stands with different damage degrees.

Table 2. Fisher test data on changes in mean defoliation of pine trees over the periods of damage and recovery.

Stand	Kind of	Statistical parameters of F – test					
group	variation between	SS	df	MS	F	F crit.	p
Period of damages							
Slightly damaged	tree diameter groups	1458	6	243	1.67	2.13	0.127
	tree condition classes	1125	3	375	2.58	2.64	0.053
Moderately damaged	tree diameter groups	2814	6	469	2.38	2.13	0.029
	tree condition classes	2071	3	690	3.49	2.63	0.016
Severely damaged	tree diameter groups	15111	6	2518	11.06	2.12	0.000
	tree condition classes	29025	3	9675	51.78	2.63	0.000
Period of recovery							
Slightly damaged	tree diameter groups	3365	6	561	6.41	2.13	0.000
	tree condition classes	8706	2	4353	28.24	3.02	0.000
Moderately damaged	tree diameter groups	2618	6	436	3.56	2.13	0.002
	tree condition classes	16227	2	8113	47.15	3.01	0.000
Severely damaged	tree diameter groups	2598	6	433	2.74	2.13	0.013
	tree condition classes	4656	1	4656	14.27	3.87	0.000

trees increased by 2-3 and 1.5 times, respectively. Needle losses of the trees that had been severely damaged were the least – only 17% or mean defoliation of these trees increased only 1.2 times.

In the group of moderately damaged stands increase in defoliation among different tree condition classes and relative diameter groups was less statistically significant ($p<0.03$), whereas in the group of slightly damaged stands it was significant ($p>0.05$).

Decrease in Tree Crown Defoliation Over the Period of Recovery

F-test statistics indicate that in the recovery period, *i.e.* from 1996 to 1999, decrease in mean defoliation of trees from different tree condition classes and relative diameter groups in all stand groups differed statistically significantly ($p<0.05$) (Table 2). It indicated that tree crown recovery from different groups occurred in the same way despite stand damage intensity. Therefore, analysis was performed by pooling all the data on tree crown recovery from all stands. Crowns of the severely damaged trees recovered most rapidly. Crown conditions of only 5.7% of these trees over a 4-year period remained stable, 65.8% moved into the class of moderately damaged trees, 12.4% into the class of slightly damaged trees, and only 16.1% died.

79% of the moderately damaged trees recovered (moved into condition classes of slightly and not defoliated trees) and 20% of these trees remained in the same class. Only 1% of these trees moved into the class of severely damaged or dead trees. More than half of the slightly damaged trees moved into the class of healthy (not defoliated) trees, the rest remained in the same class. No dead trees were registered in this tree condition class over the 4-year period.

Tree crown recovery rate was related to both needle mass that remained from 1995 and relative tree diameter. Positive relationships indicated higher crown recovery rate when tree diameter was bigger and defoliation higher. Created multidimensional non-linear regression model significantly explained more than 47% of the changes in crown recovery rate ($p<0.05$):

$$R = -1.31 + 0.19\times F - 4.38\times Dr + 0.14\times \times Dr\times F - 0.18\times \frac{F}{1+16\times\exp(-0.05\times F)} \quad (1)$$

$$r^2=0.467$$

where: R- crown recovery rate (% per year); F- crown defoliation (%); Dr – relative stem diameter.

"Mirror effect" in defoliation changes from tree decline to recovery was detected. If over the period of damage the largest trees, crown condition of which had been better than that of the other, were damaged most rapidly, then over the period of recovery, their crown recovery rate was the most intensive. The difference in recovery rate over the 4-year recovery period between the suppressed trees and holdovers, defoliation of which over the period of damage made 40%, was negligible (1.3 times), whereas when defoliation made 75%, the recovery rate increased from 5.6% per year for the suppressed trees to 13% per year for the holdovers (Fig. 3). The difference in recovery rate made 2.3 times.

Tree Mortality

Our results and those of others [11-13] suggest that tree defoliation degree has a significant impact on tree mortality. The higher the level of crown damage, the higher the probability of the tree death. Over the considered period, *i.e.* from 1992 to 1999, the number of dead trees in slightly and moderately damaged stands made approximately 4.8%, and 5.5%, respectively, which did not exceed the mean value for pine stands in Lithuania. In severely damaged stands, tree mortality was almost threefold higher and made 15.2%. However, the highest number of dead

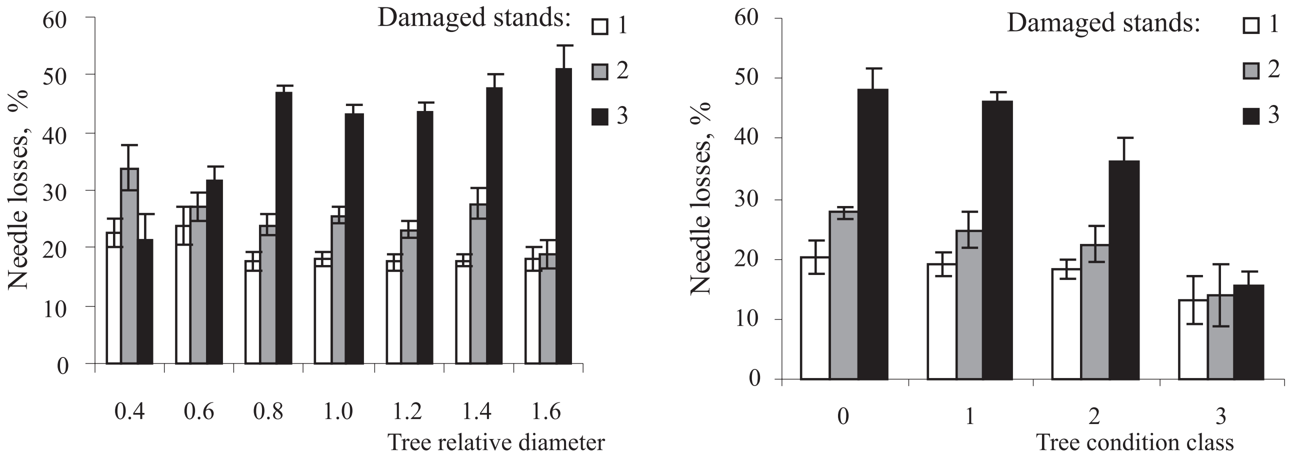

Fig. 2. Increase in defoliation of the trees (1992-95) in stands with different damage degrees.
Tree condition classes: 0- healthy; 1- slightly; 2- moderately; 3- severely damaged; Damaged stands: 1– slightly; 2– moderately; 3– severely.

trees was recorded in the group of the suppressed trees (relative diameter Dr=0.4-0.6) due to what mean relative diameter of dead trees made approximately 0.7, irrespective of stand damage degree.

Over the period of tree damage, tree condition of which had already been declined, *i.e.* defoliation exceeded 60% due to the effect of natural (meteorological factors, competition) and anthropogenic (acid deposition and ambient ozone) factors. Mortality of these trees over the 4-year period made approximately 30-40% (Fig. 5). Over the period of recovery trees severely damaged by pine sawfly died first as well. However, probability of death was considerably lower. Only 15-20% of these trees died over the 4-year period.

Despite the above-mentioned threshold for crown defoliation, above which crown recovery of a tree becomes impossible or a tree should inevitably die, was not detected. Even in the case of 95% defoliation, recovery of more than 30% of these trees was recorded and their mean defoliation over the 4-year period decreased to 56%.

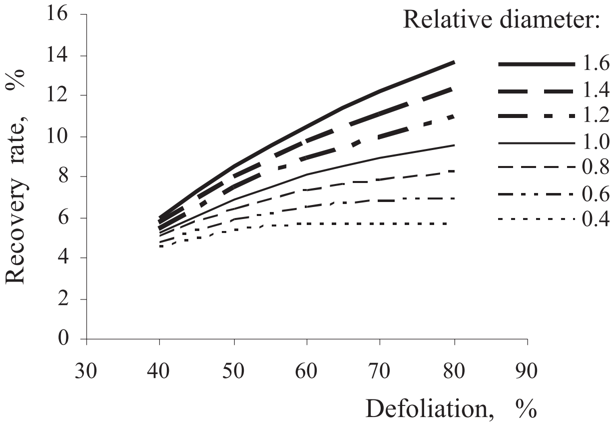

Fig. 3. Foliage recovery rate (% per year) of damaged pines

Discussion

The outbreak of pine sawflies in southern Lithuania enabled us to investigate tree crown damage, and recovery rates in relation to relative tree diameter in stands exhibiting different degrees of damage. The obtained results allowed presenting to forest managers data on tree response to suffered needle losses caused by sawflies and planning of the forest treatments in damaged areas.

Our findings corroborate with most of the common assumptions on pine needle herbivore outbreaks. Pine stands on infertile and well-drained soils [14], stands already affected by unfavourable climatic and anthro-

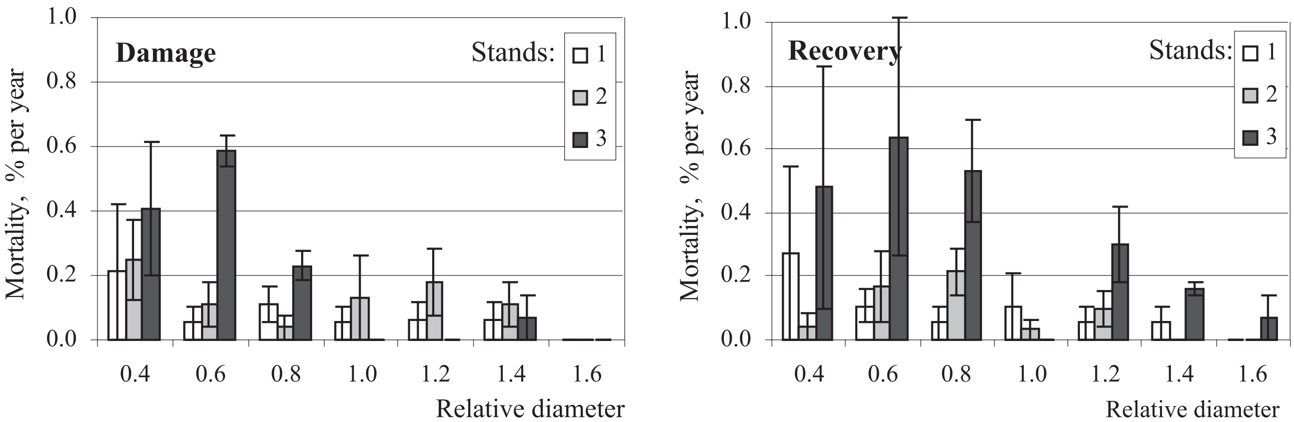

Fig. 4. Tree death intensity in different diameter groups over the period of damage (1991-1995) and recovery (1996-1999). Stands: 1– slightly; 2– moderately; 3– severely damaged.

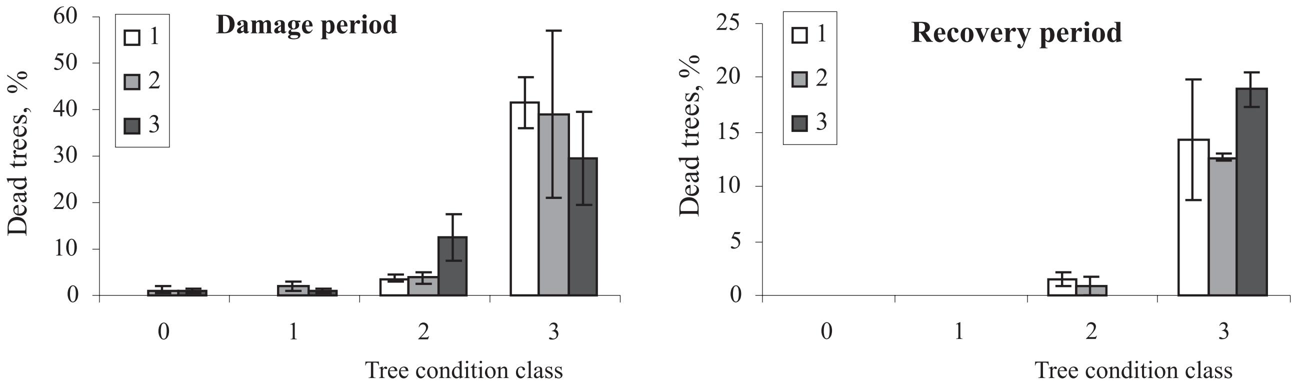

Fig. 5. Tree death intensity in different condition classes over the period of damage (1991-1995) and recovery (1996-1999).

pogenic factors [5-7] are highly preferred by sawflies. Moreover, holdovers and dominant trees in such stands are most defoliated by sawfly [8, 15, 9]. The results of our study revealed that when a population of pests does not reach the peak value and mean defoliation of the stand does not reach 40%, the suffered needle losses of all pines make on average up to 20%, irrespective of their relative diameter or crown condition. When pest population reaches the peak and mean defoliation of the stand exceeds 60%, the largest trees with biggest needle biomass become highly pest prefered and their needle losses are the most severe.

Investigation of the probability of tree death was one of the principal parts of this study. Scientists do not have unified opinion on the tree crown recovery process. Some of them state that a possibility for a tree to recover exists even after the repeated intensive damage caused by pine sawfly [11, 16], while others think that after repeated damage trees are not capable of recovery [17]. Forestry treatments such as application of the insecticide should make the possibility of recovery of the severely damaged stands more realistic. In the southern part of Lithuania biological insecticide Foray-48B was applied against pine sawfly. However, today it is difficult to evaluate the significance of this treatment. The fact is that in 1995, *i.e.* a year before the application of the insecticide, the level of pine defoliation in severely damaged stands decreased while in moderately damaged stands it remained at the same level. These observed changes indicate that the treatment could have already been a little late as recovery of the damaged stands started before it. It follows from the data in Fig. 1 that peak sawfly density may typically continue for 3 years until crown recovery starts.

Much is written that continuous needle damage causes substantial mortality, typical rates of which makes up to 25% [17] and in some cases reach 75% [11]. Mostly large trees suffer from mortality [9]. Our results were rather contrary. Distribution of the dead trees in diameter groups indicated higher probability of death of suppressed and co-dominant trees than of holdovers and dominant, irrespective of stand damage degree. The same mean diameter of dead trees in stands with different damage degree means that even in the case of intensive damage, tree mortality occurs by self-thinning strategy, *i.e.* suppressed trees die first. Whether or not the sawfly accelerated succession by early removal of trees that would have died from self-thinning is a question for further investigation. Significant decrease in mortality of trees in these stands in subsequent years could prove this statement. The obtained results allow making an assumption that needle losses suffered due to pine sawfly reinforce the negative effects of other natural and anthropogenic factors. Higher probability of death than recovery (Fig. 5) of severely damaged trees over the damage period could be presented as proof of this assumption. Based on the results we can state that there is no threshold for Scots pine tree crown defoliation above which crown recovery of the trees becomes impossible. Crown recovery of more than a quarter of severely damaged trees was recorded even in the case of 90% defoliation. The higher or lower probability of the tree recovery when the impact of the causative stress is over should be considered.

It is noteworthy that tree mortality over the first two years (1994-1995) of pest outbreak could have had dual – likely and possible additional effect on recovery of crown conditions, especially in severely damaged stands where tree mortality is almost twofold higher than in slightly and moderately damaged stands (Table 1). The likely decrease in mean defoliation occurred due to the fact that in computing of mean value of tree defoliation for 1996, when dead trees for the year 1995 were not taken into account. Only trees which died in 1996 (100% defoliation) included computing mean defoliation values for this year [10].

Possible improvement of crown conditions could have occurred due to death of dominant trees (Dr=1.0-1.2) and hold-overs (Dr>1.2). This process could have actually reduced tree competition and increased resistance to sawfly damage. Consequently, probability of tree crown recovery is related to higher availability of nutrient matter [18], light and water [19], which indicates that fertilization of such stands instead of their cutting could be one of the most acceptable treatments in pine stands damaged by pine sawfly.

Detected regularities in Scots pine condition changes and mortality probability under the effect of environmental stresses allow considering the necessity of forestry treatments. To avoid financial and ecological losses in agreement with other authors [22] we suggest analyzing each tree condition decline using the classical principles of physiopathology and forest science in general instead of supporting the hypothesis that severely damaged stands are not capable of recovery. Clear cuttings of the severely damaged stands could be approved only in cases when first bioindicative signs of total stand destruction are visible. To cut or to fertilize severely damaged stands is a question to be dealt with in the future.

Conclusion

In Scots pine stands when pine sawfly population did not reach its peak value and tree mean defoliation did not reach 40%, the suffered needle losses of all pines made up to 20% at an average irrespective of their relative diameter or crown condition. In cases when population increased and tree mean defoliation exceeded 60% the largest trees with biggest needle biomass were more pest preferred and their suffered needle losses were the most serious.

Tree crown recovery rate was significantly and directly related to both: suffered needle losses and relative tree diameter. However, only availability of nutrient matter, light and water are the key factors contributing to the 2.5 times higher crown recovery rate of severely damaged (defoliation 75%) holdovers than suppressed pines.

The greater the crown defoliation, the higher the probability of the tree mortality. However, mean relative diameter of dead trees made an average 0.7 irrespective of stand damage degree. The highest number of dead trees was recorded in the group of the suppressed trees.

Pine sawflies are the secondary key factor resulting in tree mortality reinforcing the negative effect of the unfavorable climatic factors and environmental pollution. Twofold higher probability of death of severely damaged trees over the damage period than recovery proves our assumption.

Scots pine trees have proven to be much more resistant than expected. There is no threshold for crown defoliation above which crown recovery of a tree becomes impossible or a tree should inevitably die.

References

1. BLANK L. W., ROBERTS T.M., SKEFFINGTON R.A. New perspectives of forest decline. Nature. **336**, 27, **1988**.
2. AUCLAIR A.N.D., WORREST R.C., LACHANCED. MARTIN H.C. Climatic perturbation as a general mechanism of forest dieback. In: P.D. Manion and D. Lachance D. (eds.), Forest decline concepts. St. Paul.Minnesota, pp. 38-58, **1992**.
3. CHAPPELKA A.H. FREER-SMITH P.H. Predisposition of trees by air pollutants to low temperatures and moisture stress. Environmental Pollution. **87**, 105, **1995**.
4. KLAP J. M., OUDE VOSHAAR J. H., DE VRIES W., ERISMAN J. W. Effects of Environmental Stress on Forest Crown Condition in Europe. Part IV: Statistical Analyses of Relationships. Water, Air, and Soil Pollution. **119**, 387–420, **2000**.
5. SPEIGHT M.R. AND WAINHOUSE D. Ecology and management of forest insects. Clarendon Press, Oxford, UK, pp. 374, **1989**.
6. HOUSTON D.R. A host-stress-saprogen model for forest dieback-decline diseases. In: P.D. Manion and D. Lachance D. (eds.), Forest decline concepts. St. Paul.Minnesota, pp. 3-25, **1992**.
7. GAN J. Risk and damage of southern pine beetle outbreaks under global climate change. Forest Ecology and Management. **191**, 61, **2004**.
8. SOMVIELE D.B., LYYTIKÄINEN-SAARENMAA P. AND NIEMELÄ P. Sawfly (Hym., Diprionidae) outbreaks on Scots pine: effect of stand structure, site quality and relative tree position on defoliation intensity. Forest Ecology and Management. **194**, 305, **2004**.
9. LYYTIKÄINEN-SAARENMAA P., NIEMELÄ P AND ANNILA E. Growth responses and mortality of Scots pine (Pinus sylvestris L.) after i pine sawfly outbreak. In IUFRO Proccedings, Forest insect population dynamics and host influences. pp. 81-84, **2003**.
10. UN-ECE. Manual on methods and criteria for harmonised sampling, assessment, monitoring and analysis of the effects of air pollution on forest, 3rd edition by the Programme Coordinating Centres Hamburg and Prague, **1994**.
11. LANGSTRÖM B., ANNILA E., HELLQVIST C., VARAMA M., NIEMEL P. Tree Mortality, Needle Biomass Recovery and Growth Losses in Scots Pine Following Defoliation by Diprion pini (L.) and Subsequent Attacks by Tomicus piniperda (L.). Scandinavian Journal of Forest Research. **16**, 342, **2001**.
12. DOBBERTIN M., BRANG P. Crown defoliation improves tree mortality models. Forest Ecology and Management. **141**, 271, **2001**.
13. EID T., TUHUS E. Model for individual tree mortality in Norway. Forest Ecology and Management. **154**, 69, **2001**.
14. KOUKI J., LYYTIKÄINEN-SAARENMAA P., HENTTONEN H., NIEMELA, P. Cocoon predation on diprionid sawflies: the effect of forest fertility. Oecologia. **116**, 482, **1998**.
15. NEGRON J.F., POPP J.B. Probability of ponderosa pine infestation by mountain pine beetle in the Colorado Front Range. Forest Ecology and Management. **191**, 17, **2004**.
16. WITHAM T.G., MASCHINSKI J., LARSON K.C., PAIGE K.N. Plant responses to herbivory: the continuum from negative to positive and underlying physiological mechanisms. In: Plant –animal interactions. Evolutionary ecology in tropical and temperate regions, J. Wiley and Sons, New York, pp. 227-256, **1991**.
17. KULMAN H.M. Effects of insect defoliation on growth and mortality of trees. Annual Review of Entomology. **16**, 289, **1971**.
18. ANTTONEN S., PIISPANEN R., OVASKA J., MUTIKAINEN P., SARANPAA P. VAPAAVOURI E. Effects of defoliation on growth, biomass allocation, and wood properties of Betula pendula clones grown at different nutrient levels, Canadian Journal of Forest Research. **32**, 498, **2002**.
19. COLEY P.D., BRYANT J.P., CHAPIN F.S. Resource availability and plant antiherbivore defence. Science (Washington). **230**, 895, **1985**.
20. AMMAN G.D., LOGAN J.A. Silvicultural control of mountain pine beetle: prescriptions and the influence of microclimate. Am. Entomol. **44**, 166, **1998**.
21. BERRYMAN A.A. Theoretical explanation of mountain pine beetle dynamics in lodgepole pine forests. Environ. Entomol. **5**, 1225, **1976**.
22. KANDLER O., INNES J.L. Air pollution and forest decline in Central Europe. Environmental pollution. **2** (90), 171, **1995**.