Relationship between Scots Pine Individual Tree Mortality and Tree Vigor Indicators in the Polluted Environment

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Abstract

Dependence of individual tree mortality probability on tree growth intensity (diameter increment) and crown defoliation is analysed in the article. Even-aged Scots pine (*Pinus sylvestris* L.) forests, located in the surroundings of one of the biggest air pollution sources in Lithuania, mineral fertilizer plant 'Achema' (55°05'N; 24°20'E) were the main focus of these investigations. Multiple growth dependent logistic individual tree mortality models were elaborated and it was established that the tree mortality probability increases exponentially along with an increase in crown defoliation, however the rate of increase is rather different at different stand age and at the different diameter increment. In general, at the same defoliation level the probability of individual tree mortality was detected to be much higher for trees of lower growth rate, *i.e.* for trees of lower vitality. However, the relative increase in tree mortality probability with an increase in crown defoliation was faster for trees of higher growth rate. The impact of crown defoliation on the tree mortality rate increases with the aging of stands. Tree mortality probability exponentially decreases along with increase of tree growth rate (diameter increment); however for damaged (defoliated) trees dependence of tree mortality probability on the intensity of tree growth is much less pronounced.

Key words: polluted environment, tree growth, individual tree mortality, crown defoliation

Introduction

Tree mortality is a fundamental aspect of forest dynamics. Despite mortality importance, ecological processes of individual tree mortality are poorly understood, since they often result from a complex of multiple biotic and abiotic environmental factors that occur consecutively in time (Bigler and Bugmann 2003). From the ecological point of view, tree mortality can be described in terms of growth-dependent and growth-independent factors (Harcombe 1987, Pedersen 1998, Ozolincius *et al.* 2005). Growth-dependent mortality characterizes long-lasting effect affecting tree vigour, while growth-independent factors directly lead to tree death (Franklin *et al.* 1987).

Ecologists and foresters have long recognized that tree mortality risk increases as growth rates declines (Monserud 1976). Numerous studies indicated rather strong correlation between tree growth and mortality (Buchman *et al.* 1983, Kobe 1996, Wyckoff and Clark 2000, Bigler and Bugmann 2003) and the diameter increment has been frequently used as individual tree mortality predictor (Monserud 1976, Buchman *et al.* 1983, Hamilton 1990, Yao *et al.* 2001, Yang *et al.* 2003). It was established that reduced increment of stem diameter usually indicates increased tree mortality probability. The results of different investigators have demonstrated that the diameter increment is an important tree vigour variable in predicting individual tree mortality (Pacala *et al.* 1996, Dobbertin and Biging 1998, Yang *et al.* 2003).

Crown defoliation is another important tree vigour indicator (Innes 1993). There is a strong positive relationship between crown defoliation and subsequent growth (Kramer 1986, Salemaa and Juloa-Sulonen 1990, Petras *et al.* 1993, Ozolinčius 1998, Juknys *et al.* 2002). Dobbertin and Brang (2001) have showed that crown defoliation results in increased tree mortality and could considerably improve the prediction ability of tree mortality models.

Air pollution acts like long-term lasting factor decreasing tree vitality and predisposing to the accelerated death in a polluted environment. There are many studies on pollution caused changes of tree growth and the impact of tree defoliation on tree increment (Kramer 1986, Soderberg 1991, Juknys *et al.* 2003, Petras *et al.* 2004, Stravinskiene 2004); however, taking into account that tree death is a comparatively rare and stochastic event, and investigation of the mortality process is more complicated than investigation of tree growth, data on the tree mortality process in a polluted environment are very scarce. The goal of our study is to analyse the relation between Scots pine (*Pinus sylvestris* L.) individual tree mortality rate and tree vigour indicators (diameter increment and crown defoliation) in the polluted environment.

Materials and methods

Even-aged Scots pine (*Pinus sylvestris* L.) forests, located in the surroundings of one of the biggest air pollution sources in Lithuania, mineral fertilizer plant 'Achema' (55°05'N; 24°20'E) were the main focus of these investigations.

'Achema' was founded in the central part of Lithuania at the confluence of the rivers Neris and Sventoji. The production of mineral fertilizers started in 1965 and was gradually expanded until 1978 when Nitrophoska, the most polluting department, was constructed and the total annual atmospheric emissions reached almost 40 thousand tons (Juknys *et al.* 2002). Nitrogen fertilizers produced by fixing atmospheric nitrogen at 'Achema' consume large amounts of energy. During the process major pollutants CO (9,874 t y^{-1}), SO_2 (4630 t y^{-1}) and NO_x (3,862 t y^{-1}) are emitted to the atmosphere together with large quantities of NH_3 (3734 t y^{-1}) and mineral dust (13,860 t y^{-1}) (Brazauskiene and Janulis, 1984).

The first signs of forest damage in the area surrounding 'Achema' were noticed by 1972, but this problem became extremely acute in 1979, after a very hard winter when obvious signs of forest damage in the direction of prevailing winds were recorded at a distance of up to 10–12 km, and the coniferous forests completely died within 2–3 km from the pollution source. Despite the reduction of emissions, as a result of different pollution mitigation measures implemented in 'Achema', the zone of damaged forests expanded up to 20–25 km in the direction of prevailing winds by the end of the 1980s (Armolaitis, 1998). Emissions were further reduced after a serious accident, which led to the closure of the Nitrophoska department in 1989. Total annual emissions of 'Achema' were reduced almost eightfold from the beginning of the 1980s up to the middle of the 1990s. The annual emissions of 'Achema' have slightly increased over the last several years and nowadays do not exceed 6–7 thousand tons (Juknys *et al.* 2002).

A network of permanent plots was established in 1981 in the surrounding Scots pine forests and investigations lasted for more than 20 years. A three-stage sampling pattern was used for collecting field materials: 1) sampling of research stands; 2) sampling of circular plots within each research stand; 3) sampling of trees for more detailed measurements of tree stem and crown indicators and tree ring analysis (Juknys *et al.* 2002). The research stands were systematically sampled at a different distance from the pollution source in a downwind direction along the southwest-northeast gradient.

Twelve circular sample plots were established in each research stand. The sample plots were distributed in a systematic way – according to a grid. The location of the first sample plot was chosen randomly. The area of the circular sampling plots was determined to contain on average 15–20 trees, and depending on stand density the size of the sample plots varied from 100 to 800 m^2 (Juknys 1990). The tree stem diameter was permanently re-measured and crown defoliation estimated for all sampled trees (150–200 trees per research stand) each 5–6 years at the end of summer (July, August).

The European forest monitoring methodology was used to estimate tree condition (crown defoliation), and five defoliation classes were distinguished: class 1 (conditionally healthy trees) – defoliation up to 10%; class 2 (slightly damaged trees) – defoliation 11–25%; class 3 (moderately damaged trees) – defoliation 26–60%; class 4 (severely damaged trees) – defoliation 61–99%; class 5 (crown defoliation 100%) – dead trees (UN/ECE 1994). Instead of a rather rough classification, defoliation has been evaluated with the 5% accuracy since 1990.

Mean periodical diameter increment used in our study was calculated as a difference of later and earlier tree diameter measurement divided from the period (years) between measurements (Monserud 1976, Buchman *et al.* 1983, Hamilton 1986, Yao *et al.* 2001).

Data on fourteen damaged 23–85-year-old Scots pine stands situated at different distances from the pollution source (2.9–20.1 km) were used for this study. Main dendrometric indicators of investigated Scots pine stand are presented in Table 1.

Relations between the individual tree mortality (survival) rate and different tree and stand variables were investigated using multivariate logistic models:

$$P_m = (1 + \exp(b_0 + b_1 x_1 + \ldots + b_k x_k))^{-m}, \qquad (1)$$

where P_m is the probability of tree survival over the period of m years (mortality is calculated as $1 - P_m$); b_i is the coefficient of the model; x_i is the explanatory variables.

The parameters of the models were estimated by the maximum likelihood method (Hosmer and Leme-

Table 1. General characteristic of investigated stands in the vicinity of fertilizers plant 'Achema' (P – pine, S – spruce, B – birch)

No.	Distance from plant (km)	Species composition	Age (y)	Height (m)	Breast height diameter (cm)	Stand density (trees/ha)	Basal area (m^2/ha)	Volume (m^3/ha)	Annual mortality rate (%)
1	11.8	95P5S	23	10.2	10.9	2690	10.2	55.1	3.59
2	5.7	100P	25	13.1	10.5	3120	10.1	54.3	3.73
3	2.9	65P35B	30	12.4	11.8	1680	12.3	78.7	2.48
4	10.1	82P18B	33	16.0	15.4	1315	10.2	82.6	2.35
5	6.1	94P6B	34	12.8	11.1	2530	10.8	73.4	2.58
6	10.9	99P1S	52	22.9	22.6	793	14.2	151.9	1.37
7	6.8	73P26S1B	57	15.1	17.8	825	14.3	110.1	0.99
8	10.1	94P6B	58	23.0	26.1	512	11.8	126.3	1.05
9	5.3	82P16B2S	60	25.6	26.2	542	12.7	139.9	1.30
10	10.3	91P5S4B	60	22.8	27.2	472	12.2	130.5	1.27
11	20.1	100P	61	22.6	25.0	895	26.6	284.6	1.12
12	3.6	100P	64	18.2	24.0	338	10.0	89.0	1.51
13	6.9	97P3B	69	21.9	25.7	690	18.5	192.4	1.73
14	11.9	94P6S	85	25.1	24.4	706	10.9	125.4	2.34

show 1989) on the basis of the data on the average annual mortality rate during the entire period of investigation and the data of explanatory variables at the beginning of investigations. Since defoliation classes were used for the assessment of tree crown defoliation at the beginning of investigations and only from 1990 defoliation has been evaluated with the 5% accuracy, data on defoliation for 1990 and later were used to evaluate the mean defoliation values of different defoliation classes. The following figures were obtained: 7.2% for class 1; 21.1% for class 2; 38.2% for class 3, and 78.0% for class 4. These figures were used as tree defoliation values for trees of the different defoliation classes.

The MATLAB software was used to fit the models. The significance of the parameters in the model was estimated by the likelihood ratio (LR) statistics:

$$LR = -2 \ln (L_0 / L_1), \quad (2)$$

where L_0 is the likelihood function without the explanatory variable and L_1 is the likelihood function with the explanatory variable.

The LR has an asymptotic χ^2 distribution with one degree of freedom (Hosmer and Lemeshow 1989), therefore explanatory variable x is insignificant (at the 0.05 significance level) for tree mortality if LR < 3.84. The likelihood ratio statistics were used for testing the significance of multivariate logistic model as well. In this case, the LR has an asymptotic χ^2 distribution with the k degree of freedom, where k is the number of independent variables in the model (Hosmer and Lemeshow 1989).

The assessment of the fit was made using Pearson chi-square statistics and Nagelkerke pseudo R^2. An independent variable has to be divided into k intervals for this procedure.

Pseudo R^2 statistics provide a logistic analogy to R^2 in linear regression. Nagelkerke pseudo R^2 (Nagelkerke 1991) was defined as:

$$R_N^2 = \frac{1-(L_0/L_1)^{2/n}}{1-(L_0)^{2/n}} \quad (3)$$

R_N^2 estimates an increase in the likelihood function independently of sample size n, therefore this statistics can be used to compare the logistic models, fitted on different data sets.

Data on the relations between the individual tree mortality rate and selected mortality predictors are presented in Table 2. Though an essential reduction in the closeness of relations (R_N^2) between the tree mortality rate and diameter increment (DIN) and conversely slight increase in the closeness of relations (R_N^2) between the tree mortality rate and crown defoliation (F) can be noted with the aging of stands, statistically significant relations (χ^2>3.84) between individual tree mortality rate and investigated tree vigour indicators are characteristic of all investigated Scots pine stands (Table 2), and both variables were included as predictors into logistic multiple tree mortality models.

Table 2. Dependence of the tree mortality probability on diameter increment (DIN) and crown defoliation (F)

Variable	Stand age (year)						
	23	25	30	33	34	52	57
	R^2_N / χ^2						
DIN	0.538 / 107.2	0.445 / 88.16	0.607 / 146.6	0.519 / 98.97	0.418 / 75.71	0.349 / 61.32	0.387 / 62.13
F	0.118 / 39.20	0.119 / 28.73	0.136 / 24.54	0.189 / 17.85	0.134 / 16.50	0.160 / 19.50	0.163 / 16.13
Variable	Stand age (year)						
	58	60	60	61	64	69	85
	R^2_N / χ^2						
DIN	0.327 / 41.26	0.139 / 20.23	0.187 / 29.92	0.263 / 33.14	0.247 / 31.54	0.319 / 36.73	0.140 / 17.23
F	0.228 / 27.19	0.165 / 16.09	0.214 / 21.38	0.275 / 28.09	0.211 / 23.52	0.229 / 24.31	0.233 / 28.72

Taking into account that the severity of damage depends on the distance of investigated Scots pine stands from the pollution source (Table 1), a very important question is – whether the same level of tree crown defoliation implies the same probability of tree mortality in differently damaged stands. Only in the case of the positive answer the data of investigated stands can be combined and the general logistic mortality model elaborated.

In order to answer this question, investigated stands were separated into two groups – heavily damaged (average crown defoliation over 38%) and slightly damaged stands (average crown defoliation below 21%), and the zero hypothesis that the differences in individual tree mortality rate at the same tree crown defoliation level (same defoliation class) are not statistically significant for differently damaged stands was tested using the chi-square test. Four research stands (735 sampled trees) composed the heavily damaged group and six research stands (1,193 sampled trees) comprised the group of slightly damaged stands. The zero hypothesis can be rejected at the 0.05 significance level when the chi-square test value is more than 3.84.

The estimated values of chi-square statistics for different defoliation classes were 1.03 (class 1), 1.76 (class 2), 1.87 (class 3) and 0.35 (class 4). All these values are less than 3.84 and zero hypotheses can be accepted with the 0.05 significance level. A conclusion can be made that same defoliation level results in the same mortality probability independently on the general stand damage level. The data on differently damaged stands can be joined and, consequently, the general logistic mortality model elaborated.

Therefore the mortality rate is different in the stands of different age, all the investigated stands were divided into four groups: two 23–25-year-old stands, three 30–34-year-old stands, three 52–58-year-old stands and five 60–69-year-old stands. An individual tree mortality model was elaborated for each group and the diameter increment and crown defoliation were included as mortality predictors.

23–25 year

$$P_{10} = 1 - (1 + \exp(-2.87 + 0.037\,F - 0.292\,DIN))^{-10}, \quad \chi^2 = 24.8 \qquad (4)$$

30–34 year

$$P_{10} = 1 - (1 + \exp(-4.04 + 0.032\,F - 0.255\,DIN))^{-10}, \quad \chi^2 = 48.5 \qquad (5)$$

52–58 year

$$P_{10} = 1 - (1 + \exp(-4.58 + 0.033\,F - 0.218\,DIN))^{-10}, \quad \chi^2 = 111.3 \qquad (6)$$

60–69 year

$$P_{10} = 1 - (1 + \exp(-4.09 + 0.022\,F - 0.150\,DIN))^{-10}, \quad \chi^2 = 31.2 \qquad (7)$$

The parameter estimates and the estimates of standard error of parameters are listed in Table 3. As seen from Table 3, all regression coefficients were statistically significant ($p < 0.05$) and had a tendency to decrease with increasing stand age.

Table 3. Estimated parameters for mortality models at different age groups

Parameters	23-25 y		30-34 y		52-58 y		60-69 y	
	value	p	value	p	value	p	value	p
Intercept	-2.870	0.060	-4.035	0.004	-4.575	<0.001	-4.098	<0.001
F	0.037	0.020	0.032	0.020	0.033	<0.001	0.022	0.001
DIN	-0.292	0.001	-0.255	0.010	-0.218	<0.001	-0.150	0.013

A general growth dependent tree mortality model was elaborated for the Scots pine stands of different age (Equitation 8) on the basis of tree mortality models for different age groups. Considering that the limits of tree diameter increment were different in stands of different age, this variable was standardized, *i.e.* the diameter increment of individual tree was divided by the average diameter increment of each age group, respectively.

$$P_{10} = 1 - (1 + \exp(2.55 + 0.018 \times A - (0.099 + 0.001 \times A) \times SDIN + (0.044 - 0.0003 \times A)\,F))^{-10}, \qquad (8)$$

where, A – stand age, y; SDIN – relative diameter increment;. F – crown defoliation, %.

The graphical view of the dependence of the estimated tree mortality probability values on crown defoliation and relative diameter increment at different Scots pine stand age is presented in Figures 1 and 2.

As seen from Figure 1, the tree mortality probability increases exponentially along with an increase in crown defoliation, however the rate of the increase is rather different at different stand age and at the different diameter increment. In general, at the same defoliation level the probability of individual tree mortality was much higher for trees of lower diameter increment, *i.e.* for trees of lower vitality. However, the relative increase in the tree mortality probability with an increase in crown defoliation was faster for more vital trees (Figure 1). The 10-year mortality probability increased 2.3 times for trees of the lowest vitality (SDIN = 0.2) in the 20-year-old Scots pine stands, when defoliation increased from 5 to 75%. At the same time, the mortality probability of the most vital trees (SDIN = 2.6) increased almost 7 times within the same range of crown defoliation. A similar pattern is typical of older Scots pine stands as well, however differences in the impact of defoliation on the trees of different vitality (different diameter increment) decrease with increasing stand age. For example, with an increase in crown defoliation from 5 to 75%, 10-year mortality probability increased 4.4 times for the trees of lowest vitality (SDIN = 0.2) and 5.1 times for the most vital trees (SDIN = 2.6) in the 80-year-old stands.

The impact of crown defoliation on the tree mortality rate increases with the aging of stands (Figure 1). For example, the 10-year mortality probability for trees of average vitality (SDIN = 1) and minimal defoliation (5%) is 0.302 in the 20-year-old stands and increases up to 0.900, *i.e.* about three times as defoliation increased to 75%. At the same time, in the 80-year-old stands, more than a fourfold increase in the probability of mortality for trees of the average vitality was noted in the same range of defoliation.

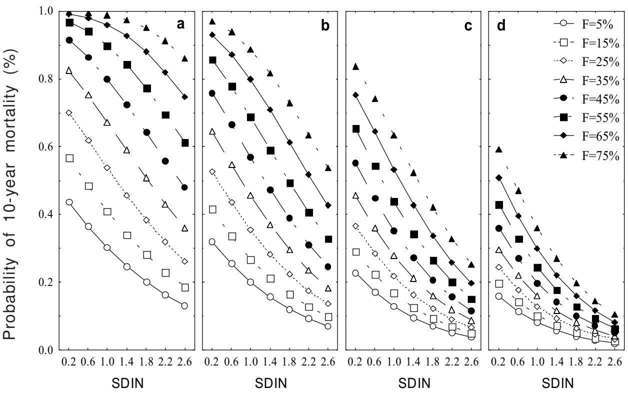

Figure 1. Dependence of 10-year individual tree mortality probability on standardized diameter increment (SDIN) at the different level of crown defoliation (age of stand: a – 20 year, b – 40 year, c – 60 year, d – 80 year)

Other cut of elaborated multiple logistic model, *i.e.* – dependence of mortality probability on the standardized diameter increment at different level of crown defoliation is presented in Figure 2. The data presented in Figure 2 show that in the case of relatively healthy trees (F = 5%) 10-year mortality probability decreased 3–4 times along with increase of standardized diameter increment (SDIN) and this tendency almost did not depend on stand age.

In the case of damaged (defoliated) trees the dependence of tree mortality probability on intensity of tree growth (SDIN) is less pronounced and is rather different in stands of different stand age. For example, with an increase in SDIN from 0.2 to 2.6 for heavily defoliated trees (F = 75%), the probability of tree mortality decreased 1.2 times in the 20-year-old stands, 1.8 times in the 40-year-old stands, 2.5 times in the 60-year-old stands, and 3.5 times in the 80-year-old stands.

To test the behaviour of elaborated models and to estimate its possible bias, actually observed mor-

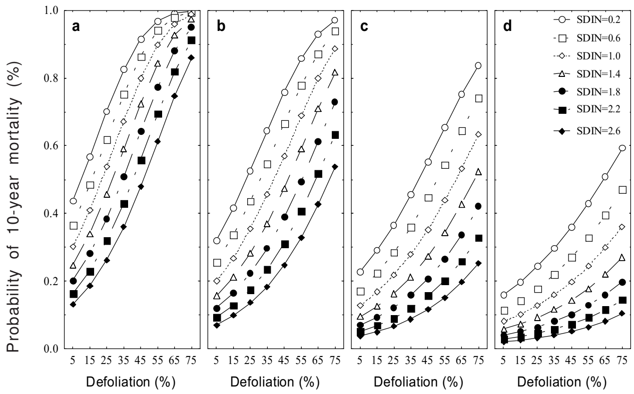

Figure 2. Dependence of 10-year individual tree mortality probability on crown defoliation at the different standardized diameter increment (age of stand: a – 20 year, b – 40 year, c – 60 year, d – 80 year)

tality was plotted against predicted model output. Predicted and observed tree mortality rate and estimated 95% confidence intervals of predicted tree mortality at the different diameter increment groups and crown defoliation classes for Scots pine stands of different age are presented in Figures 3 and 4.

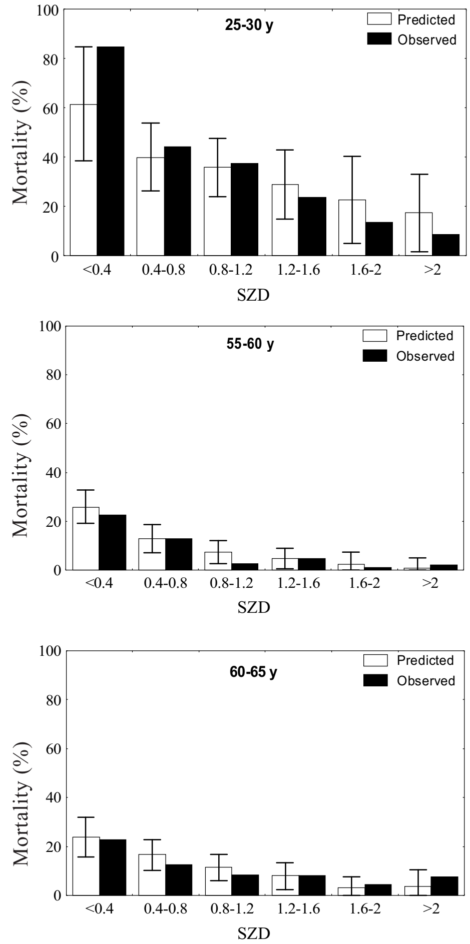

Figure 3. Predicted and observed 10-year mortality over diameter increment at the different stand age

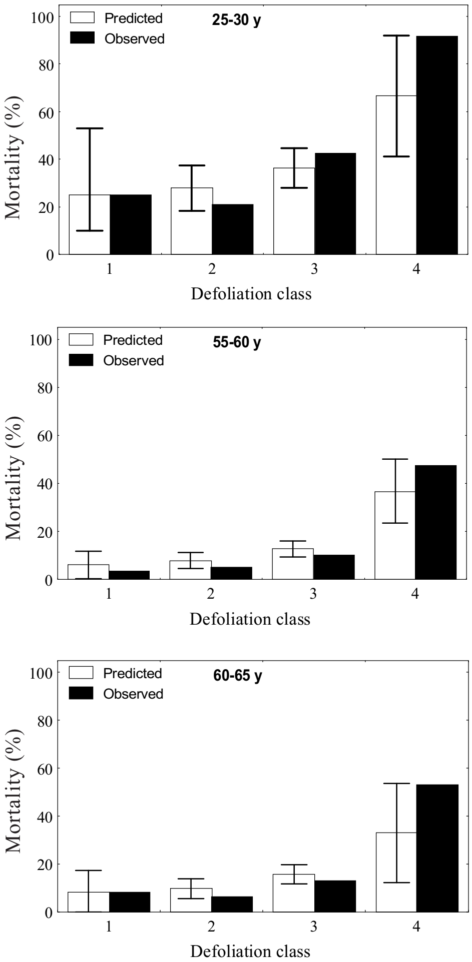

Figure 4. Predicted and observed 10-year mortality over defoliation classes at the different stand age

Despite some more expressed differences in the class of lowest diameter increment and class of highest defoliation, the mortality rate of observed trees fell into confidence intervals of predicted tree mortality in all diameter increment and crown defoliation classes.

Discussion and conclusions

A growth-mortality function is an empirical summary of the complex relationship involving environmental stress, growth, and mortality risk. Slow growth indicates low vigour and risk from a variety of agents (Wyckoff and Clark 2000). As indicated by Buchman *et al.* (1983), the diameter increment of a tree strongly influences its mortality rate. Dobbertin and Biging (1998) reported that mortality rates were higher for trees with reduced growth rates. Results of our research suggest a strong exponential relationship between growth and mortality (Figure 1). Wyckoff and Clark (2000) tested three alternative methods for estimating tree growth-mortality functions. All three methods gave similar results, the probability of tree mortality decrease exponentially with an increase in the diameter increment. However, our investigations have shown that in the case of damaged (defoliated) trees the dependence of the tree mortality probability on the intensity of tree growth is less pronounced and is rather different in stands of different age (Figure 2).

Crown related variables, such as crown width, crown ratio or crown defoliation, have been commonly used to model tree growth and mortality (Wykoff *et al.* 1982, Monserud and Sterba 1999, Dobbertin and Brang 2001). Numerous studies showed increased tree mortality rates following insect defoliation (Crow and Hicks 1990, Steinman and MacLean 1994, Gottschalk *et al.* 1998). Dobbertin and Brang (2001) presented findings that mortality rates increase exponentially with an increase in crown defoliation.

Although the relationship between pollution caused changes in tree growth and the impact of tree defoliation on tree increment has been shown in a number of studies (Kramer 1986, Soderberg 1991, Juknys *et al.* 2003, Petras *et al.* 2004, Stravinskiene 2004), investigations of the tree mortality process in the polluted environment are very scarce. Our previous research on the relations of individual tree mortality with tree variables in the polluted environment showed an exponential increase in the individual tree mortality probability with increasing crown defoliation, however, the rate of increase being rather different in different age and diameter classes (Juknys *et al.* 2006). Similar findings were found analysing the relation between the individual tree mortality and tree vigour indicators (diameter increment and crown defoliation) in the polluted environment, where the rate of mortality increase is rather different at different stand age and diameter increment. In general, at the same defoliation level the probability of individual tree mortality was detected to be much higher for trees of lower growth rate, *i.e.* for trees of lower vitality. However, the relative increase in the tree mortality probability with increasing crown defoliation was faster for trees of higher growth rate.

General conclusion could be made, that indicators of increased mortality of damaged (defoliated) trees should be considered while assessing losses in forest productivity in the polluted environment.

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ЗАВИСИМОСТЬ ВЕРОЯТНОСТИ ОТПАДА ДЕРЕВЬЕВ ОТ ПОКАЗАТЕЛЕЙ ЖИЗНЕСПОСОБНОСТИ СОСНЫ ОБЫКНОВЕННОЙ В УСЛОВИЯХ ЗАГРЯЗНЕННОЙ ПРИРОДНОЙ СРЕДЫ

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Резюме

Проведены исследования зависимости вероятности индивидуального отпада деревьев от интенсивности роста и дефоляции кроны в одновозростных древостоев сосны обыкновенной (*Pinus sylvestris* L.), произростающих в зоне воздействия завода минеральных удобренний 'Achema' (55°05'N; 24°20'E). Разработаны множественные логистические модели вероятности индивидуального отпада деревьев. Установленно, что вероятность отпада деревьев возрастает экспонентно в зависимости от повышения дефолиации кроны, но повышение вероятности отпада деревьев зависит от возраста и прироста по диаметру. При одинаковом уровне дефоляции кроны вероятность индивидуального отпада деревьев выше у деревьев с медленным ростом, однако более значительное повышение вероятности отпада деревьев с увеличением дефоляции кроны установленно на деревьях с более быстрым ростом. Влияние дефоляции кроны на интенсивность отпада деревьев возрастает с увеличением возраста древостоев. Вероятность отпада деревьев уменьшается экспонентно с увеличением интенсивности роста, однако, у поврежденных деревьев зависимость вероятности отпада деревьев от интенсивности роста выраженна менее явно.

Ключевые слова: загрезненная среда, рост деревьев, индивидуальный отпад деревьев, дефолиация кроны.