Crown Indicators and their Relationship with Acid Deposition: Forest Health Monitoring Case Study in Baltic States

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Primary (crown density, foliage transparency) and integrated (total crown losses) tree crown indicators according to Forest Health Monitoring (FHM) program have been chosen as the main parameters indicating forest health in the Baltic States. Geographical Information System Arc Info has been used for the analysis of spatial changes of these indicators and their relations with acid deposition (sulphur and nitrogen). It is determined that northward increase of crown density of Scots pine (*Pinus sylvestris L.*) and birch (*Betula spp.*) is statistically significant ($p<0.05$). Data on total crown losses of the main tree species and groups demonstrate a clear trend along geographical gradient, decreasing from south to north. Deposition of sulphur and nitrogen tend to decrease distinctly in the same direction. It was determined that the correlation between the FHM crown indicators and deposition is not strong, however, in most cases, statistically significant ($p<0.05$). The correlation between deposition and Scots pine crown indicators (primary and integrated) indicated the greatest statistical significances. The relations of total crown losses with sulphur deposition occurred to be stronger than with nitrogen.

Key words: Forest health monitoring, crown density, foliage transparency, total crown losses, acid deposition

Introduction

At the very beginning of the 1970's some investigators warned of a danger of increasing environmental pollution and possible forest damages on a regional scale (Wentzel 1971, Smith 1974), however, this message did not receive proper attention. First signs of forest damages on a regional scale were noticed in Germany (Knabe 1981, Bauer 1982) and similar messages were published in other countries of Central and Western Europe very soon (Bernadzki *et al.* 1983, Karl 1986). In the mid of 1980s, damaged forests in Germany covered about 50%, Switzerland – 34%, Czechoslovakia – 27%, Austria – 26%, Poland – nearly 10% of total forest area (Postel 1984, Giesen 1985). Forest decline on the wide areas of Europe and North America has become one of the most serious ecological problems. Since the middle of the eighties regional damages of forests have been recorded in Lithuania and other Baltic countries (Ozolincius and Stakenas 1996).

Some uncertainty remains specifying the main causes of the forest decline on a regional scale. A number of reports suggest that the main causes along with environmental pollution are unfavourable climatic conditions, forest pest invasions, different diseases, and improper forest management (planting of monocultures, concentrated clear cutting, fertilization, etc.) (Ballach 1984, Bonneau 1986, Nys 1989, Auclair *et al.* 1992, Houston 1992). In contrast to this approach, there are statements that forest decline on a regional scale results from the whole complex of natural and anthropogenic stressors but air pollution is the main causative factor, while others only strengthen the impact of pollutants (Schoper and Hradetzky 1984, Fuhrer 1985, McLaughlin 1985). Long-range transboundary pollution and environmental acidification are implicated as major causes of forest decline on a regional scale in Europe (Knabe 1981, Braker and Gaggen 1984). Some of the investigators report the most negative direct effect of sulphur and nitrogen compounds on leaves and needles (Moosmayer 1984, Wentzel 1985). Others stress indirect effect of these compounds, i.e., when acid deposition not only increases soil acidity, but also stimulates the formation of toxic aluminium compounds (Ulrich 1981, Hutchinson *et al.* 1986). Recently considerable attention has been paid to the study of acid deposition and their critical loads (Nilsson and Grennfelt 1988, Bobbink *et al.* 1992).

Forest Health Monitoring (FHM) program in the U.S.A. was developed in the response to increasing concern for the forest health in light of the potential effects of atmospheric pollutants, global climate change, and a variety of insect, disease, and other stressors (FHM Field Methods Guide 1996). To adapt this program in the Baltic States, the international USA – Baltic project of FHM was initiated in 1993 and sponsored by USA Environmental Protection Agency mainly. The professionals of Estonia, Latvia and Lithuania were introduced and trained in FHM field methods, provided with modern equipment and data loggers. The first four-year cycle of FHM fieldwork activity lasted from 1994 to 1997.

The main objective of this paper is to analyse spatial distribution of FHM crown indicators and to estimate the relationship of these indicators with acid deposition.

Materials and methods

The Baltic States – Estonia, Latvia and Lithuania - are situated in the transition zone between the West European maritime and the East continental climates (Fig. 1). Scots pine *(Pinus sylvestris L.)*, Norway spruce (*Picea abies Karst.*) and birch (*Betula pendula Roth.* and *Betula pubescens Ehrh.)* prevail in the Baltic States and constitute about 80% of the total forest area. Pine stands in all the three states constitute about 40% of all the forests, spruce stands – nearly one fourth and the area of birch stands ranges from 20% in Lithuania to 30% in Estonia.

In 1994-1997 a total of 413 Forest Health Monitoring (FHM) plots were established in the Baltic States: 57 in Estonia, 160 in Latvia and 196 in Lithuania. Spatial distribution of the established FHM plots is presented in Fig 1.

Fieldworks in the Baltic States were performed according to the FHM manual. The sampling design was based upon a triangular grid of 40 km^2 hexagons. The plot location co-ordinates for Baltic countries were provided from the U.S.A. GIS laboratory and fieldwork manual was adapted to the Baltic States (FHM Field Methods Guide 1996).

According to FHM Guide, each FHM plot consists of four circular subplots that are spaced 36.6 m apart (Fig. 2). The key sampling unit for most tree measurements is the 1/60 ha subplot. The centre of subplot 1 is also the centre of overall FHM plot. The centres of other subplots are located in the following directions

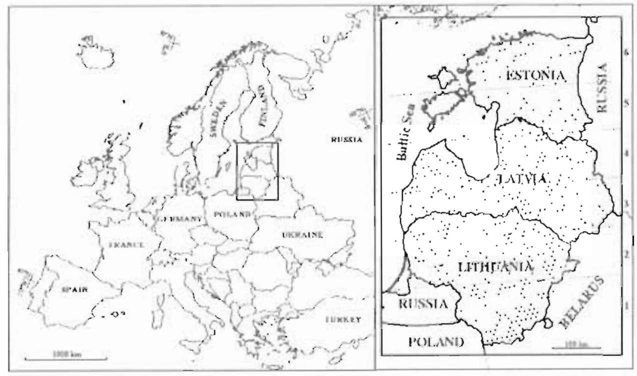

Figure 1. Location of the established FHM plots. 1-6 are numbers of latitudinal sectors

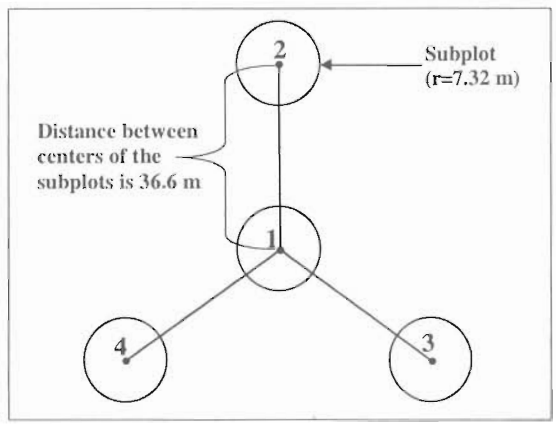

Figure 2. Forest Health Monitoring Plot

from subplot 1: subplot 2 - 0°, subplot 3 - 120° and subplot 4 – 240°.

Two quantitative crown indicators - crown diameter, live crown ratio and three qualitative indicators - crown density, crown dieback and foliage transparency were measured or assessed for the subplot trees greater than 12.7 cm in diameter.

According to the FHM field method guide, live crown ratio is determined by the ratio of live crown length to total live tree height. Trees with higher crown ratios are typically viewed as healthier and faster growing. Crown diameter is defined as the average of two measurements – widest crown diameter and perpendicular to this one. Crown density estimates the crown condition in relation to a normal, healthy, forest tree and also serves as an indicator of expected growth in the near future. Crown density is the amount of crown branches, foliage, and reproductive structures that block light visibility through the crown. Higher crown density is an indicator of faster growth, while lower crown density indicates slower growth. Foliage transparency is defined as the amount of skylight visible through the live, normally foliated portion of the crown or branches. Changes in foliage transparency occur as a result of current damage frequently referred to as defoliation, or from reduced foliage resulting from stress during preceding years. Foliage transparency is estimated in 5 percent classes based on the live, normally foliated portion of the crown and branches using the crown density - foliage transparency card. Crown dieback is defined as branch mortality, which begins at the terminal portion of a branch and proceeds toward the trunk and/or the base of the live crown. Dead branches in the lower portion of the crown are assumed to have died from competition and shading and are not considered as a part of crown dieback, unless most of the branches above that point are dead. Qualitative crown indicators are evaluated by two field crewmembers. They should stay about ½ to 1 tree height apart from the tree in order to obtain a good view of the crown (FHM Field Methods Guide 1996). Qualitative crown indicators are considered to be the main tree health indicators.

To standardize tree crown indicators a special methodology was elaborated (Juknys and Augustaitis 1996). All the three qualitative crown indicators were integrated into one to combine information of different tree species in major tree groups and group totals. Reduced crown density and increased foliage transparency and dieback were considered as crown losses (losses of branches, shoots and foliage) due to the effects of different internal (competition) and external (environmental pollution, insects, diseases etc.) factors. This integrated crown indicator was named total crown losses (TCL) and was assessed in the following way:

[1] $$TCL = 100 - \left\{(100 - DNL) \times \frac{(100 - FTL)}{100} \times \frac{(100 - DBL)}{100}\right\}$$

where:

DNL - crown losses due to reduced crown density (losses of branches, shoots and foliage),

DBL - crown losses due to increased dieback (losses of shoots and foliage),

FTL - crown losses due to increased foliage transparency (losses of foliage).

To determine crown losses, assumption of normality is very important: what can be considered as a normal crown density, normal crown dieback, and normal foliage transparency. On the basis of FHM data, normal crown density for *Pinus sylvestris* was set at 70%, for *Picea abies* - 85% and for birch - 75%. Normal foliage transparency - for most species was determined as 5% with exception of *Picea abies* - 0%. Normal crown dieback - zero for all species.

Tree crown losses due to reduced crown density (DNL) in percent were computed:

[2] $$DNL = \frac{NCD - CRD}{NCD} \times 100$$

where NCD is normal crown density and CRD is crown density of monitored tree.

Tree crown losses due to increased foliage transparency (FTL) in percent were computed:

[3] $$FTL = \frac{FTR - NFT}{100 - NFT} \times 100$$

where NFT is normal foliage transparency and FTR - foliage transparency of monitored tree.

Crown losses due to increased crown dieback (DBL) should be assessed according to the analogous formula (3), however, taking into account, that normal dieback for all monitored species equals zero, DBL becomes equal CDB (crown dieback).

Invert distance weighed interpolation technique was chosen as the method to generate maps of primary and integrated crown indicators. Six nearest plotwise estimates were used for computing value of every point (pixel) of the investigated territory. Resolution of generated surfaces was 3x3 km, they are available as the WinNT Arc Info grids. Basic GIS information, such as administrative boundaries, main land use types, was downloaded from Baltic Sea region GIS database, developed and maintained by GRID-Arendal, Norway (GRID - Report 2000).

To determine northward changes of FHM crown indicators and annual acid deposition, the territory under investigation (from 54°35'18" to 59°14'39" north latitude) was divided into six latitudinal sectors - 100 km each. The mean values and confidence limits (p=0.05) of the main crown indicators of different tree species were estimated for each sector. The mean values of sulphur and nitrogen deposition were computed for the same latitudinal sectors as well.

The data on total (wet and dry) sulphur and nitrogen (oxidized and reduced) deposition in the Baltic States over the interval 1994–1997 were taken from the EMEP database (EMEP Summary Report 1999). It provides data on spatial distribution of acid deposition on a smaller scale (50x50 km) (Van Pul *et al.* 1995, Erisman *et al.* 1996). According to the FHM field data, the mean values of primary and integrated crown indicators were computed for each 50x50 km square and the correlation between the investigated crown indicators and sulphur and nitrogen deposition was estimated.

Fisher test was used for estimating the significance of northward changes in the main crown indicators of different tree species.

Results

Primary crown indicators

As it has already been mentioned Scots pine, Norway spruce and birch prevail in all the three Baltic States. The data on the spatial distribution of crown density of these tree species are presented in Figure 3. From this it appears that crown density of all the tree species tends to increase northward. This trend is most exhibited by pine and least by spruce.

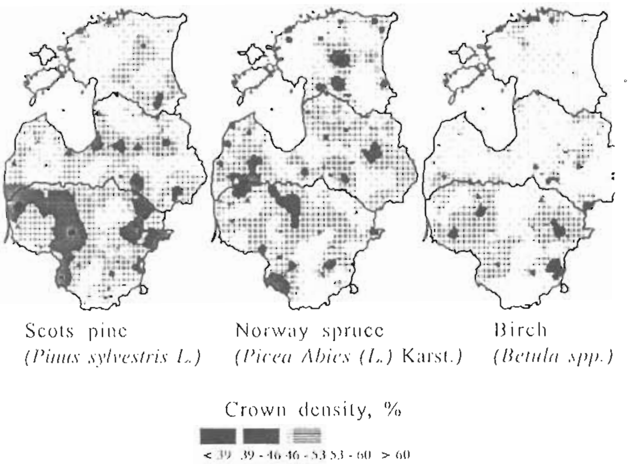

Figure 3. Spatial distribution of crown density of the main tree species in the Baltic States

The mean values and confidence limits (p=0.05) of crown density for different latitudinal sectors are presented in Figure 4 and the statistical significance of northward changes in Table 1. Crown density of Scots pine demonstrated a clear trend along the geographical gradient, increasing from south – 46.8% to north – 56.4%. F test data indicated the greatest significance of northward changes of this parameter, which made up nearly 10%. Northward changes in crown density of birch trees are a little less essential as compared with crown density change of pine trees but they are rather significant too. Only the changes in spruce crown density demonstrate no any evident trend along the geographical gradient from south to north. The exposure to forest pest invasions was the main reason for this (Ozolincius and Stakenas 1999).

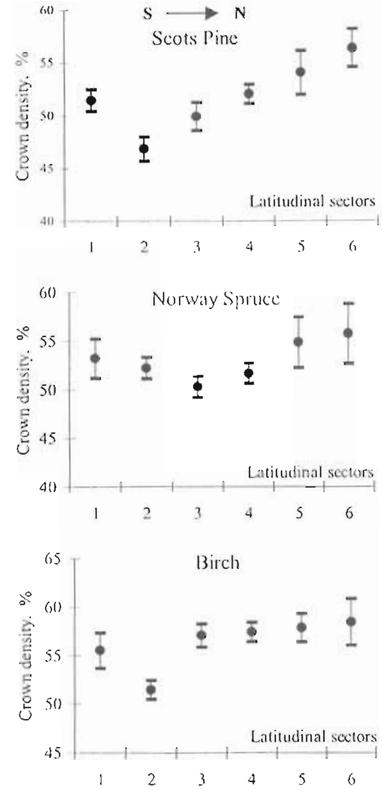

Figure 4. Crown density of the main tree species in different latitudinal sectors

It should be noted that in the first southernmost sector, the computed mean of crown density for all tree species is higher than in the next northern sector. It could be attributed to the fact that the southern part of Lithuania is most forested (over 60%), whereas the density of population and industry in this region is comparatively low.

Data on the mean crown density of tree species under investigation in different Baltic States are compiled in Table 2. From this it follows that the mean crown density of pine in Estonia (northernmost Baltic country) is by nearly 7%, that of spruce by 4% and of birch by 5% higher than in Lithuania (southernmost Baltic country).

Table 1. Fisher test data of northward changes in tree crown indicators

Tree species	Indicator	F value	p value
Scots pine	Crown density	5.52	< 0.0001
Norway spruce	Crown density	1.54	< 0.1776
Birch	Crown density	4.08	< 0.0014
Scots pine	Foliage transparency	0.63	< 0.6747
Norway spruce	Foliage transparency	1.93	< 0.0906
Birch	Foliage transparency	2.58	< 0.0268
Scots pine	Total crown losses	4.68	< 0.0004
Conifers	Total crown losses	3.97	< 0.0017
All species	Total crown losses	3.13	< 0.0087

Note: Critical F value $F(5, >100)=2.2141$ when $p=0.05$

Table 2. Mean crown density of the main tree species in the Baltic States

State	Scots Pine	Norway Spruce	Birch spp.
	Crown density, %		
Estonia	55.3±1.5	55.5±2.3	58.5±1.6
Latvia	52.3±0.7	51.7±0.8	57.1±0.9
Lithuania	48.8±0.8	51.6±0.9	53.7±0.8

The data on foliage transparency of different tree species is generalized in Figure 5. As seen from the presented map, it is difficult to single out any regularity in spatial changes of this crown indicator. In the

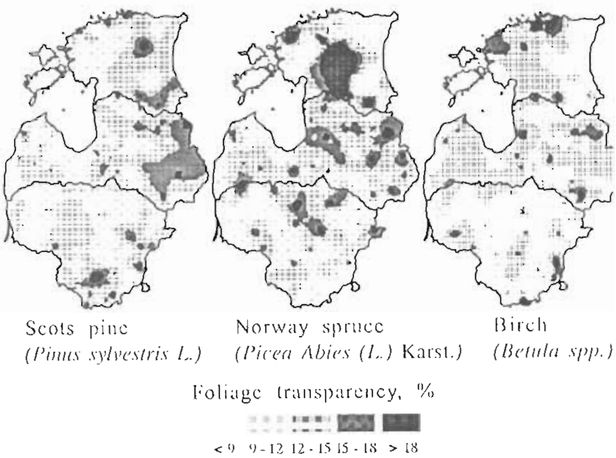

Figure 5. Spatial distribution of foliage transparency of the main tree species in the Baltic States

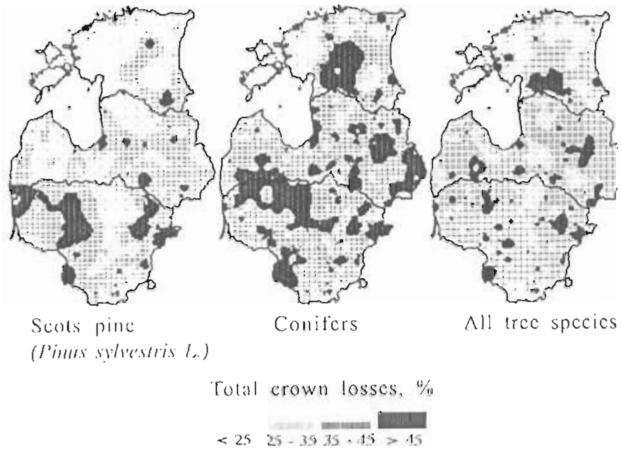

Figure 6. Spatial distribution of total crown losses of pine, conifers and all tree species

eastern part of Estonia and Latvia and in the southern part of Lithuania the increased foliage transparency of pine might be observed while in the central part of Estonia, in the north east of Latvia and in the north of Lithuania the increased foliage transparency of spruce.

Thorough analysis of the data on crown dieback had indicated that, in most cases no crown dieback rating was obtained, i.e., most frequently this indicator was equal to zero and very seldom exceeded 5%. Therefore this crown indicator was removed from the further analysis due to its insignificance.

Integrated crown indicator

Having standardized the primary crown indicators and integrated them into one – total crown losses, there was a possibility to investigate not only the crown condition of separate species, but also of major species groups (conifers and deciduous) and group totals. Integrated indicator – total crown losses were computed according to the first formula but due to insignificance of crown dieback without its second member (100-DBL).

Figure 6 reflects spatial distribution of total crown losses for pine, conifers and generally all the tree species. Total crown losses tend to obviously decline northward. The data on total crown losses of Scots pine trees demonstrated the most significant trend along the geographical gradient, decreasing from south to north (Table 1).

As indicated in Figure 7, total crown losses of Scots pine in the northernmost sector (6) constitute 30.0% and in the second southernmost sector (2) – 41.6%. As in the case of crown density (Fig. 4), the southernmost sector proves to be an exception where tree crown condition is somewhat better than in the next. Total crown losses of all conifers tend to decline northward, but the maximum crown losses – 44% are recorded in

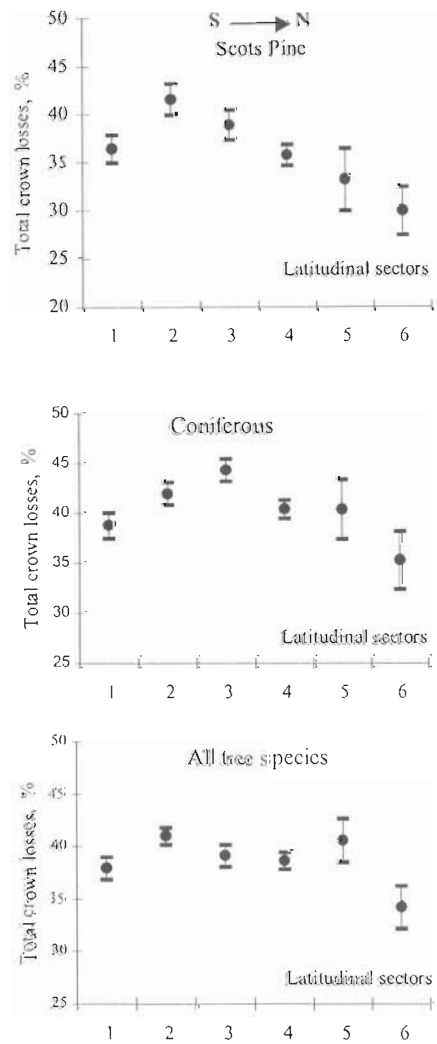

Figure 7. Total crown losses of Scots pine, conifers and all tree species in different latitudinal sectors

sector No. 3. Northward the changes in total crown losses of all the tree species are less essential than these in pine trees and conifers but statistically they are significant. Presumably it might be explained by the fact that the response of different tree species to the effect of external factors is rather different.

Having compared total crown losses between the Baltic States separately (Table 3), we had found that total crown losses of Scots pine in Lithuania were by 8% higher in comparison with Estonia and by nearly 3% higher than in Latvia. After generalizing the data of all conifers, these differences decreased, nevertheless crown losses in Lithuania were by more than 4% higher than in Estonia. According to the data on all tree species, this difference was even lower (2.5%), however, statistically significant ($p<0.05$).

Table 3. Total crown losses in the Baltic States

State	Scots Pine	Conifers	All tree species
	Total crown losses, %		
Estonia	31.4±2.2	37.5±2.3	37.0±1.7
Latvia	36.7±0.9	41.1±0.7	38.8±0.7
Lithuania	39.4±1.1	41.6±0.8	39.5±0.6

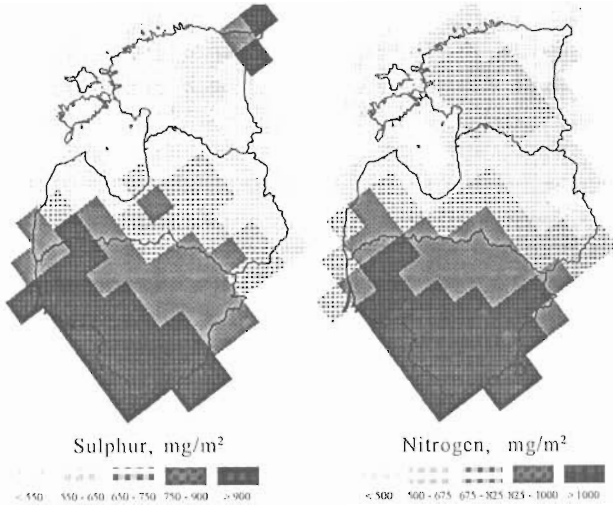

Figure 8. Annual sulphur and nitrogen deposition in the Baltic States (Based on EMEP data 1997)

The relationship between crown indicators and acid deposition

Acid deposition is considered to be the main anthropogenic factor determining forest decline on a regional scale in Europe. Due to the joint international efforts and economic decline in the East European countries sulphur deposition have decreased nearly 2-3 times (EMEP Summary Report 1999). For example, at the end of the 1980s the annual total (wet and dry) load of sulphur in Lithuania constituted about 20-25 kg per hectare, and was reduced up to 7-10 kg at the end of the 1990s. A decrease in nutrient nitrogen load was not so impressive. At the end of the 1980s general annual load of oxidised and reduced nitrogen in Lithuania constituted about 15 kg per hectare, while at present about 10-12 kg (Sopauskiene and Jasinevіciene 1997).

On the basis of EMEP data (1999), spatial changes in sulphur and nutrient nitrogen deposition on the investigated territory have been analysed (Fig. 8). The data presented in this map show rather evident decrease in sulphur and nitrogen deposition northward. As in the case of crown indicators, the mean sulphur and nitrogen deposition for all the 6 latitudinal sectors was computed.

As it follows from Figure 9, annual sulphur deposition in the southernmost sector constitutes about 1000 mg/m^2 and decreases very obviously northward. In the northernmost sector annual sulphur deposition exceeds only 600 mg/m^2. Northward trend of nitrogen deposition is rather similar, i.e., total deposition of oxidized and reduced nitrogen on the investigated northern territory is 1.5 times lower than in the south.

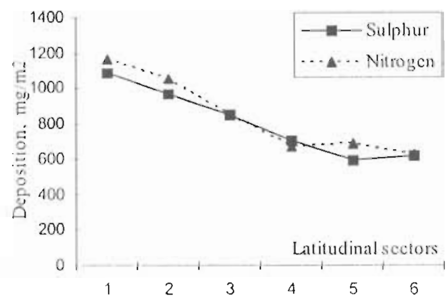

Figure 9. Sulphur and nitrogen deposition in different latitudinal sectors (Based on EMEP data, 1997)

Furthermore, we attempted to investigate the effects of sulphur and nitrogen deposition on forest health. As mentioned above, the correlation between the investigated crown indicators and acid deposition was estimated and presented in Table 4.

Table 4. Correlation between tree crown indicators and deposition of sulphur and nitrogen

Deposition	Crown density		
	Scots Pine	Norway Spruce	Birch spp.
Sulphur	-0.395*	-0.217	-0.233*
	0.000	0.069	0.034
Nitrogen	-0.349*	-0.062	-0.267*
	0.002	0.602	0.016

* marked correlation is significant ($p<0.05$).

Table 4 illustrates that the relationship between crown indicators and deposition of sulphur and nitrogen is not strong, however, in most cases, statistically significant ($p<0.05$). Despite the evident reduction of sulphur deposition in the last decade, crown indicators correlate stronger with sulphur deposition than with that of nitrogen. Based on the data presented in Figures 3-9 we conclude that crown indicators of Scots pine statistically significantly correlate with acid deposition loads, whereas weak and statistically insignificant correlation is typical of spruce crown indicators. It can be in part explained by the fact that the exposure of spruce stands to pest invasions has been shown to affect the condition more than environmental pollution. After grouping all the species, we had found that the relationship between tree health and pollutant loads appeared to be weaker than in the case of Scots pine, however, the relationship with sulphur deposition was statistically significant.

Discussions

Interpretation of the collected data is one of the most important stages of monitoring and to a great extent affects the value of monitoring system itself. Actually crown indicators reflect not only tree condition and its changes but also the potential of their productivity. Studies have been mostly concentrated on the effects of tree crown condition, in most cases on tree crown defoliation and tree increment. The results obtained are rather controversial. Some investigators do not find any statistically significant relation between crown defoliation and tree increment (Kohler and Stratman 1986). The others state that obvious tree increment decrease begins when defoliation becomes lower than 20-30% (Schweingruber 1985, Krause *et al.* 1986, Braker and Gaggen 1987) or even 50% (Franz *et al.* 1986). Other researchers present contrary results - they find that the decrease in tree increment usually starts before obvious signs of crown defoliation can be detected (Philips *et al.* 1977, Kontic and Winkler-Seifert 1987). Our investigations, carried out in damaged Scots pine stands have indicated, that the relationship between crown defoliation and tree increment is not strong (usually correlation coefficient does not exceed 0.4-0.5), but statistically significant ($p<0.05$) (Juknys and Jancys 1998).

Having investigated the relationship of FHM crown indicators with stem diameter increment, we had found that the correlation of crown density and foliage transparency with stem increment was rather similar to that of crown defoliation ($R=0.4–0.5$). The relationship between crown dieback and tree increment was weak and statistically insignificant (Juknys and Augustaitis 1996).

According to H.Kramer (1986) both qualitative and quantitative crown indicators (crown diameter, length, surface area, etc.) should be taken into account when analysing the relationship between crown indicators and tree increment. Our investigations suggest (Juknys and Augustaitis 1996) multiple regression model, which includes total crown losses as an integrated indicator of crown quality, and crown surface area, as a general crown quantitative indicator, and explains up to 50% of tree diameter increment variance ($R^2= 0.35-0.50$).

In the field works of Forest Health Monitoring, along with crown quality indicators (crown density, foliage transparency, crown dieback), two quantitative crown indicators – crown diameter and live crown ratio are determined. The latter shows the ratio of crown length to the total tree height. However, during the field works the height of trees is not measured. Therefore there is no possibility to determine general quantitative indicators such as crown volume or crown surface area. Thus biological interpretation of the data on crown indicators proves to be more complicated.

To evaluate stand productivity and timber volume, it is necessary to have the data on the assessment of statistically significant tree height. Thus it would be worthwhile to supplement the program of Forest Health Monitoring field works with the measurements of tree height.

While analysing the dependence of crown indicators on air pollution and acid deposition, the investigators fail to find more close correlation (Schweingruber 1985, Nelleman and Frogner 1994, Klap *et al.* 1997). An attempt is frequently made to interpret it as a proof that forest decline on a regional scale is caused not by environmental pollution, but by other factors. Our results have indicated that the correlation between crown indicators and acid deposition is not strong ($R=0.25-0.40$), however, statistically significant ($p< 0.05$). The main reasons for rather weak correlation between crown indicators and environmental pollution are the following:

1. The data on environmental pollution usually are not determined by direct measurements on the forest monitoring plots, but computed applying different mathematical models, most frequently implying different errors.

2. To date the assessments of crown indicators have largely been carried out by visual estimation thus subjectivity and systematic errors are feasible. Additional problems arise when indicators subjectively assessed by different experts in different countries are integrated and analysed together.

3. Crown condition is affected not only by environmental pollution, but also by many natural factors, which might considerably transform the response of trees to the effects of the pollutants.

4. The synergistic effects of different pollutants, their compounds and mixtures are not sufficiently investigated and assessed.

Upgraded models and detailed deposition maps (Van Pul *et al.* 1995, Erisman *et al.* 1996) have offered an opportunity to enhance assessment precision of the pollution effects on a regional scale on forest health and growth. Further efforts to improve evaluation of crown indicators and a decrease in subjectivity and systematic errors should contribute to a more accurate assessment of the effects of environmental pollution on the forests too. More thorough studies of the effects of natural factors on the forest health (Klap *et al.* 1997) might considerably reduce information noise and facilitate detection of the anthropogenic signal. With respect to the complexity of the investigated relationships and factors determining these relationships, further research should reduce some of the uncertainties in assessing the effect of environmental pollution on the forests.

Conclusions

1. Crown density of Scots pine tends to increase northward. In the second southernmost sector the mean crown density of Scots pine constitutes 46.8% and in the north – 56.4 %, i.e., by nearly 10% less. The changes in crown density of birch are insignificantly expressed, however, the general trend is similar and statistically significant. Spatial changes in foliage transparency are not so evident and no regular pattern can be detected.

2. Total crown losses of Scots pine tend to decrease from south – 41.6% to north – 30%. After grouping conifers and all the tree species, it had been found that spatial trends of total crown losses were not so obvious, however, a northward decrease in total crown losses was statistically significant in all cases.

3. Correlation between the FHM crown indicators and acid deposition is not strong, however, in most cases statistically significant ($p<0.05$). The primary and composite Scots pine crown indicators correlate with sulphur and nitrogen deposition most closely.

4. The relationship of primary crown indicators and total crown losses with sulphur deposition appeared to be stronger than that of nitrogen.

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ПОКАЗАТЕЛИ КРОН ДЕРЕВЬЕВ И ИХ СВЯЗЬ С КИСЛОТНЫМИ ОСАДКАМИ ПО ДАННЫМ МОНИТОРИНГА ЗДОРОВЬЯ ЛЕСА БАЛТИЙСКИХ СТРАН

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Резюме

Первичные и комплексные показатели крон деревьев использовались как основные показатели состояния лесов, внедряя Американскую программу мониторинга здоровья леса (FHM) в Балтийских странах. Анализируя территориальные изменения параметров изучаемых показателей и их связь с кислотными осадками, использовались географические информационные системы ArcInfo. Установлено, что увеличение густоты крон сосны обыкновенной (*Pinus sylvestris L.*) и берез (*Betula spp.*) на северном направлении является статистически значимой ($p<0,05$). Общие потери крон основных видов деревьев и их групп демонстрирует явный тренд по географическому градиенту уменьшаясь с юга на север. Выпадения серы и азота также уменьшается в этом направлении. Установлено, что корреляция между FHM показателями состояния крон с кислотными осадками является не очень высокой, но статистически значимой ($p<0,05$). Корреляция между выпадениями серы и показателями состояния крон сосны является наиболее значимой. Зависимость общих потерь крон от выпадения серы сильнее, чем от азота.

Ключевые слова: Мониторинг здоровья леса, густота кроны, прозрачность кроны, общие потери кроны, кислотные осадки