UNITED
NATIONS

E

Economic and Social
Council

Distr.
GENERAL

EB.AIR/WG.1/1999/9
9 June 1999

ENGLISH ONLY

ECONOMIC COMMISSION FOR EUROPE

EXECUTIVE BODY FOR THE CONVENTION ON
LONG-RANGE TRANSBOUNDARY AIR POLLUTION

Working Group on Effects
(Eighteenth session, Geneva, 25-27 August 1999)
Item 5 (a) of the provisional agenda

CAUSE-EFFECT RELATIONSHIPS IN FOREST CONDITION
State of current knowledge

Summary report presented by the Coordinating Centre of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests */

I. INTRODUCTION

1. The environment is being subjected to a variety of stresses and continuous change in the physical and chemical characteristics of ouratmosphere. While some of the stressors and changes are due to natural processes, many of them are the result of collective human behaviour. From the interrelations between natural and anthropogenic stress factors it can be seen that in practice it is not always possible and easy to distinguish triggering, accompanying and inciting factors, acting together on a certain forest stand.

2. Forest decline is a complex disorder: it is not a disease, although disease organisms are often involved. The forest decline process originates from multiple stresses acting sequentially, concurrently, synergistically, or cumulatively on a forest stand and results in progressive loss of tree vigour. Mortality is common, although affected trees may recover subsequent to the removal of the inciting stresses.

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3. However, one common feature of stress impact is the uneconomic use of nutrients, energy, and water, leading to alterations of storage patterns in trees, soils and on the ecosystem level. In trees, the stress-activated repair and adaptation mechanisms lead to altered allocation of nutrients and energy. Branching anomalies and loss of needle and leaf biomass are the consequence of changed resource partitioning on the tree level. Impacts on the element budgets are detectable in nutrient ratios in assimilation organs of plants; in soils often a net loss of elements is detectable, and on the ecosystem level deviations from a steady state can be seen in time series of matter balances.

4. Understanding how ecosystems are changing and how these changes will alter the biological components and the regulative functions of forest ecosystems is a major concern. Two main questions arise from this:

(a) Is our knowledge of the impacts of the various stresses on complex forest ecosystems sufficient for the understanding of the main interactions in forests; and

(b) What degree of certainty is necessary to take action?

5. This document presents a short version of the report “Cause-effect-interrelations in Forest Condition” elaborated for ICP Forests and providing a comprehensive literature study of the current state of knowledge in various ecological disciplines. The full report contains the complete list of references not included in this short version.

II. ATMOSPHERIC INPUT TO FOREST ECOSYSTEMS

A. Introduction

6. Air pollution has been shown to damage vegetation including forest trees directly on leaf surfaces and via stomata and cuticula uptake. Important gaseous pollutants are ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), nitric acid vapour (HNO_3), and fluorides. Indirect impact of air pollution occurs via acidifying and eutrophying effects on the forest ecosystem. However, there are differences in sensitivity of various ecosystem types, so that critical loads have been defined for the indirect impacts of acidification by S and N deposition, as well as for eutrophication by N deposition. For direct effects critical levels of pollutant concentration in the atmosphere were defined. Both approaches aim at the identification of critical thresholds for the protection of ecosystems.

7. To find exposure-effect relationships it is important to quantify air pollution input to the ecosystems via measurements and/or modelling of air pollution concentrations and deposition. One of the most important issues for ICP Forests is to study the possible contribution of air pollution, especially long-range transported air pollution, to the damage to forest ecosystems.

B. Pathways

8. The major part of the atmospheric input reaches the forest soil via precipitation, litterfall or washoff by rain. Precipitation is enhanced at high elevated sites. On isolated hill tops, trace substance concentrations are also slightly higher, leading to 3-7 times higher wet deposition rates, compared to sites in low altitudes. In cloudwater (fog) the trace substance concentrations are 2-10 times higher than in rain water, which were deposited very efficiently onto vegetation. In central Europe, cloud events increase with height above sea level up to approximately 2000 m. Dry deposition consists of particulate and gas deposition. Some gaseous pollutants (O_3, SO_2, NH_3) can be taken up directly by the leaves, a contribution to the total load, which is often neglected in the case of S and especially N, as recent findings show. However, the magnitude of gas deposition strongly depends on surface wetness, especially for SO_2 and NH_3.

C. Air pollution data necessary for ICP Forests

9. A quantitative, process-oriented description of atmospheric input to forest ecosystems depends on knowledge on: (i) the deposition processes; (ii) the structure of the forest (tree species and height, leaf area distribution, surface roughness); (iii) the microclimate (frequency of cloud cover, precipitation, wind speed distribution); and (iv) the concentration of trace substances. Since this information is difficult to obtain for larger areas, experimental monitoring of throughfall in forest canopies is an accepted approach for the estimation of the input. However, this method cannot be used for quantifying deposition of substances with substantial internal cycling, so that measured throughfall rates - not corrected for canopy exchange - are generally not good estimates of total deposition (especially for N, K, Ca, Mg).

10. Another method is the use of deposition/transport models. Long-range transport models (LRT) can provide atmospheric concentration levels over Europe, if source and sink strengths, meteorology data, and residence times of the substances are known. The EMEP model can provide air concentrations and deposition of pollutants on a regional scale (150 km x150 km grid) using emission data, meteorological conditions and chemical transformation processes. Advanced models (e.g. EDACS) use inferential techniques to describe deposition processes, but a lot of aggregation and averaging of deposition parameters must be performed.

D. Present levels and loads of air pollution

11. The average deposition range, given in table 1, for the period 1986-1996 is based for acid deposition on data published by EC and UN/ECE in the report “Ten years of monitoring forest condition in Europe” (1997) and for N on throughfall measurements plus estimated canopy uptake rates. They should be taken as rough estimates. The actual loads on specific forest sites depend strongly on tree species, growth parameters, elevation and distance to local emission sources.

Table 1. Deposition range (1986-1996) of N and total acid deposition for different regions in Europe

	Total N in kg N/ha/yr	Total acid in kmol/ha/yr
Scandinavia	10 - 40	1 - 4
Central Europe	40 - >60	4 - >6
Western Europe	<10 - 40	<1 - 4
Eastern Europe	40 - >60	2 - >6
Southern Europe	<10 - 20	<1 - 2

12. Background levels of ozone have increased about 3 times over the 20th century, from about 20 µgm^{-3} in the 1890s to about 60 µgm^{-3} over large areas in Europe today. Also, over large areas in Europe episodes with enhanced O_3 concentrations occur frequently each summer. The critical levels for crops and forests in the form of accumulated exposure of O_3 over the threshold 40 ppb (AOT 40) are exceeded in most European regions each year. Future levels depend on the reduction of anthropogenic nitrogen oxide and volatile organics emissions.

13. The composition of sulphur (SO_4^{2-}, SO_2) in the atmosphere and thus the deposition rates are affected by long-range transport, especially in Scandinavia, where local sources are comparably small. S concentration and deposition in Europe showed a 2-6 fold increase from the beginning of the century until the 1970s, and rates have been declining since. The location of the deposition maxima shifted from the major industrialized areas of north-western Europe in 1900 to the industrialized areas of the border region between Germany, Poland and Czechoslovakia in the 1980s. Total yearly deposition in western and northern Europe has now reached the rates of 1950, which is still 3-fold that of the period 1880-1900 and still exceeds the critical loads. Nitrogen emissions have remained at a high level since the 1980s, areas with high N depositions are mostly NH_4 dominated.

14. Base cation deposition is an important factor in the calculation of critical laods for acidity. Base cation deposition derives from a number of natural and anthropogenic sources (sea salt, fires, volcanoes, soil erosion, industrial emissions). The source strength of these sources is difficult to determine and consequently also the amount of deposition. The base cation deposition is not constant in time. There has been a decrease over many parts of western Europe since the 1970s when dust control techniques were implemented. During the latest decade a new decreasing trend has been seen due to emission reductions in eastern Europe. At present, the base cation deposition is not well mapped over Europe, but wet deposition data from EMEP show the significant gradient from southern Europe to the north, which is mainly due to Saharan dust deposition.

III. EFFECTS ON PLANTS

A. Conifers

1. Introduction

15. Numerous exposure experiments have shown the damaging effects of gaseous pollutants (O_3, SO_2, NO_x, NH_3, but also acid rain/mist) on forest trees. For forest trees damage thresholds have been derived (6critical levels). However, due to different experimental designs (dose, duration & frequency of exposure, plant material, soil type, chamber type, etc.) different reactions on each scale have been described. The variability in the pattern of biochemical and physiological reaction increases with the increasing level of complexity, i.e. from the cellular level to the whole tree. Especially with subacute concentrations of pollutants linear effects are not to be expected. Numerous mechanisms (buffer, filter, detoxification and repair) are able to avoid visible damage, and *in situ* interactions with site and climatic conditions modify possible effects of air pollutants. The few long-term exposure studies (> one year) clearly show impacts of chronic subacute pollutant levels, similar to those observed at natural sites. These studies also show that the effects of one or more pollutants can be increased or impeded by the genetic disposition, the physiological state, the stage of development, and by abiotic site factors.

2. Ozone

16. Ozone is almost exclusively taken up via the stomata and the O_3 molecule affect primarily the mesophyll, the cell walls, as well as the plasma membranes. The primary damaging effect of O_3 seems to be based on disturbances of membrane integrity. The secondary damaging effect of O_3 may be caused by processes related to the synthesis and allocation of storage components. Especially in cases of chronic exposure of forest trees to ambient O_3 levels, secondary effects are mainly to be expected. Chlorophyll content, photosynthetic rate, and C allocation are often affected by O_3: net photosynthesis is generally negatively affected in several tree species after short-term O_3 exposure. Data from long-term studies (> one season) are scarce, but it seems evident that O_3 influences photosynthesis also negatively. It could be shown that chronic exposure of spruces to subacute O_3 concentrations results in a permanent impairment of stomatal regulation, resulting in increased transpiration rates.

17. Exposure to O_3 reduces partitioning of carbohydrates to roots and impair phloem transport. At many sites, spruce trees with symptoms of "montane yellowing" already display signs of visible phloem collapse and repair processes are enforced. In the long term, growth reductions of roots reduce water transport and lead to water deficiency. This may be compensated for by abscission of transpiring leaves or needles. There is great evidence for the contribution of O_3 to premature needle shedding, causing and accelerating needle chlorosis (6premature senescence). After long-term exposure to O_3, growth reductions are detected and decreases of frost tolerance. From various

symptoms it is known that they were more pronounced under nutrient deficiency conditions.

3. Nitrogen oxide and ammonia

18. Foliar uptake occurs as NO, NO_2 and NH_3, while roots take up N as NH_4^+ and NO_3^-; now also the uptake of organic N (glycine) by *P. sylvestris* and *P. abies* could be verified. The N uptake by needles can be considerable (20-50%). However, high concentrations of NO_x are phytotoxic, whereas exposure to high acute NH_3 concentration leads to morphological damage.

19. Nitrogen is - traditionally - the most limiting element for the growth of forests. A sustained increased growth of forests can only be realized if the increased N supply is balanced by the supply of other nutrients such as Ca, Mg, K, P and micronutrients. Along a European (deposition-) transection significant changes in nutrient contents and dry weights of spruce needles were observed; the ratio between nutrient content and dry weight indicates that N was immediately used for growth. This indicates a high cation demand at sites with high N loads. In Sweden, especially the K/N ratio decreased between 1985 and 1994. The enhanced growth during the last decades leads to the conclusion that fertilizer effects, due to increased N deposition, overcompensate for potential growth reductions. The highest increases of growth could be found mainly at sites with medium or poor nutrient supply, which seems to indicate that increased N deposition triggered this development. Along a European transection a significant relationship between N content of young needles and stemwood production was observed. Mostly, N-induced growth is combined with enhanced shoot growth, i.e. shoot/root ratio is enhanced, and often the height growth. For Norway spruce high N supply is accompanied by decreasing root branching density and by reduction of mycorrhizae. All this enhances the risk of snow break, storm damage, and water stress. An unbalanced N nutrition frequently leads to a decreased resistance to pests (insects, fungi). Several field studies indicate a connection of fungal infection with the N content and increased N/K ratio of leaves or needles. However, in the case of conifer decline symptoms, fungal infection seems to play a minor role.

4. Sulphur dioxide and acid rain

20. The needle surface is covered by the thin, waxy cuticle, which has many protective and regulatory effects; its integrity is therefore essential for trees. Trees are able to compensate for the impact of temporary non-toxic SO_2 concentrations via reductive and oxidative detoxification mechanisms. Acid rain increases foliar leaching, which results in reductions of foliar nutrient concentration and growth unless the loss is compensated by enhanced uptake of nutrients. Chronic exposure of conifers to ambient subacute SO_2 concentrations leads to accumulation of SO_4^{2-} in the cell vacuole as non-toxic salt deposits (with Ca^{2+}, K^+, Mg^{2+}). This effect is of most importance at forest sites poor in Mg and K supply, since the additional cation demand cannot be met.

5. <u>Synergistic reactions</u>

21. Synergistic reactions were found in exposing *P. strobus* to a combination of SO_2 and O_3, i.e. the combination of both pollutants results in an enhancement of the individual effects. Accelerated senescence is a characteristic effect for O_3 as well as for SO_2 treatment. Synergistic effects have been found also in nearly all studies concerning SO_2 and NO_2. The exposure to SO_2 increased the susceptibility of Norway spruce to frost. Accordingly, winter frost events in spruce plantations in the ore mountains exposed to acute SO_2 concentration resulted in the die-back of whole spruce plantations.

22. Additionally, studies with acid fogs showed that a direct relationship exists between the amount of S in the leaves and the ability of a tree to withstand frost. An increase in foliar S content of 0.1% caused a 2.7EC decline in frost hardiness. In highly polluted areas in southern Poland the reaction of trees to drought is much more pronounced than in lesser polluted regions in the north, i.e. the sensitivity to drought is enhanced by air pollution. It is concluded that the recuperation process actually occurring in the north eastern parts of central Europe could have been caused by interactions of favourable weather conditions and reduced air pollution since the early 1990s. Trees affected by pollutants and/or low in K and Mg supply, are predisposed to secondary attack by insects and diseases. High infection rates with *Armillaria ostoyae* were found at roots of Norway spruce after SO_2 fumigation, and enhanced susceptibility of forests to insect attacks as reaction to high SO_2 doses were reported.

B. <u>Oak and beech</u>

1. <u>Introduction</u>

23. The European beech (*Fagus sylvatica* L.) and the various oak *(Quercus)* species are economically and ecologically the most important broadleaved forest trees in Europe. During the past 3 decades, occurrence of severe oak damage has been recorded in several European countries (Russian Federation, Romania, Yugoslavia, Poland, Slovakia, Czech Republic, Hungary, Austria, Germany, Netherlands, Sweden, United Kingdom, Belgium, France, Italy, Spain, Portugal). The symptoms of oak damage were: reductions in growth; crown thinning due to abnormally increased twig abscission and die-back of buds; discoloration or yellowing of the leaves; decreased leaf size; remaining leaves arranged in tufts at the end of the shoots; epicormic shoots; slime flux at the trunks; partial necroses of bark and cambium. The various symptoms do not necessarily occur synchronously and vary in their extent.

24. Damage to beech has been reported mainly from the western parts of Europe (especially from Germany, Switzerland, Italy, France, United Kingdom). However, the beech in eastern Europe is affected as well. Besides growth reductions, the main symptoms are alterations in the branching pattern and shoot morphology, small, curled and yellowed leaves concentrated at the end of the shoots, and, ultimately, crown die-back. Compared to oak, damage showed a lesser regional extension and a lesser intensity.

2. Abiotic factors

(a) Air pollutants

(i) Oak

25. In long-term SO_2 fumigation experiments with oak seedlings, different results have been obtained. In *Q. robur,* SO_2 fumigation with concentrations even above ambient levels did not affect photosynthesis, and physiological mechanisms were capable of neutralizing the acid. In contrast, fumigation of *Q. cerris* and *Q. pubescens* with similar SO_2 concentrations resulted in decreased photosynthesis and water use efficiency and, in *Q. cerris,* in reduced foliar dry weight. The results are in accordance with the general classification of *Q. petraea* and *Q. robur* as SO_2-tolerant in contrast to *Q. ilex,* which was rated as SO_2-sensitive. In a study in the Danubian region, direct effects of SO_2 and NO_2 on the vigour of oak stands could be excluded.

26. Direct effects of NH_3 have only been reported from sites adjacent to NH_3 sources. However, in almost every oak stand of central and northern Europe, the calculated N deposition reached or exceeded the critical load for deciduous forests (15-20 kg ha^{-1} yr^{-1}). Mostly, the throughfall fluxes of NO_3^- + NH_4^+ exceeded a threshold of 15 kg N ha^{-1} yr^{-1}, thereby increasing the risk of NO_3^- leaching from the soil. In a vast number of investigations, N deposition led to measurable effects on the trees. In the majority of the investigated stands in Germany as well as in parts of Slovakia and Austria, the foliar N concentrations were above the normal level, which was partly combined with low contents of P, Mg and/or K, leading to increased N/element ratios. In northeastern France the nutrient development was studied in the annual rings of *Q. robur.* Between 1938 and 1967 the N concentrations increased, whereas those of P, K and Mg decreased. The Danubian study revealed that, in *Q. robur*, the foliar P and K concentrations decreased and the N/P and N/K ratios increased with increasing crown thinning. In northwestern Germany, the crown density of *Q. robur* correlated with the foliar Mg concentrations.

27. In northeastern Germany, the leaves of damaged oaks had low concentrations of Ca and Mg. However, close correlations between the nutrient status and the vigour of the investigated oaks could not be detected. Significant losses of Ca and Mg from oak stands, triggered by air pollution, have been established, inter alia, in Hungary, Austria, and Germany. However, no indications were found that soil chemical stress acts as a causal factor of the current oak damage, but a continuing N input is regarded as a risk to ecosystem stability due to loss of base cations and an aggravation of nutritional imbalances.

28. Studies on the effects of ozone on oaks are scarce. Long-term exposure of *Q. robur* seedlings to field-relevant O_3 levels did not cause measurable reductions of CO_2 uptake. However, reductions in shoot and root biomass of *Q. robur* seedlings were found after a 2-year exposure to an O_3-dominated mixture

of air pollutants (field-relevant concentrations). Thus far, unambiguous evidence for O_3 as a main cause of the reported oak damage is still missing.

(ii) Beech

29. *F. sylvatica* is less tolerant to SO_2. Long-term fumigation of young beeches with SO_2 (single or with NO_2 and/or O_3) resulted in: decreased foliar concentrations of Ca, Mg, chlorophyll and proteins; reduced foliar buffer capacity; deformation and discoloration of leaves, premature senescence, and reduced dry weights of roots/shoots. A combined fumigation often aggravated the effects. The impacts on growth as well as an increased leaf feeding preference by the beech weevil *Rhynchaenus fagi* were also found when the plants were exposed to non-filtered ambient air and compared to trees supplied with filtered air.

30. The deposition of N to almost every beech stand considered (central and northern Europe) reached or exceeded the critical load. Generally, in Germany and Switzerland, beech trees exhibit high or very high foliar concentrations of N and often low contents of P and Mg. However, close correlations with crown conditions were not found. With increased NH_4^+ supply, the degree of fine root mycorrhization, and the concentration of living mycorrhizae in the humic layer were decreased, but so far, correlations with tree damage were not detected.

31. Fumigation with ozone in field-relevant concentrations caused growth reductions and a decrease in chlorophyll concentrations, and affected CO_2 assimilation, and water use efficiency. Exposure of beech seedlings to O_3 dominated mixtures of air pollutants with ambient concentrations for up to three years showed a decrease in shoot and, esp. fine root biomass; enhanced leaf chlorosis; premature leaf fall; and increased susceptibility to winter frost. However, the opinion on O_3 impact differ in Europe. In Austria and Switzerland, some authors do not expect O_3 to represent a dominating stress factor, but in central Europe, the critical level of O_3 for forests is exceeded widespread. In the United Kingdom, O_3 is supposed, together with long-term effects of drought, to contribute to damage to the beech. For Germany, it is also hypothesized that O_3 renders the beech more susceptible to other stress factors.

(b) Site factors and climatic extremes

(i) Oak

32. Especially in *Q. robur,* close correlations were found between soil water relations and tree health. In the Netherlands, northwestern Germany, France and the Danubian region, oak damage was found to be increased at hydromorphic sites with fluctuating water tables. At those sites, the rooting is impaired, leading to more severe drought stress in dry periods. Generally, drought is considered to be one of the main factors for the outbreak of damage to oak during the past decades. This has been explicitly stated for Romania, Poland, the Danubian region, Italy, France, the United Kingdom, and Portugal. *Q. robur* was more severely affected by summer droughts (France). Physiologically, the

susceptibility to drought stress decreases in the sequence *Q. robur; Q. petraea; Q. pubescens; Q. ilex and Q. suber*, which fits the natural habitats of these species well.

33. Severe winter frost is regarded as one of the causal factors of oak decline in eastern and central Europe and in southern Sweden and may have had a synchronizing effect on the occurrence of decline in the eighties. In northern Germany, up to 20% of the damaged oaks exhibited stem bark necrosis which, presumably, was caused by three consecutive cold winters in the mid-eighties. Oaks with low C/N ratios in the bark show decreased frost resistance. In southern Sweden, frost damage to roots is seen as the initial cause of oak decline. In the past two decades, climatic extremes seem to have occurred more frequently in continental regions. This may explain the fact that, during this period, the first reports on oak decline came from the eastern parts of Europe.

(ii) Beech

34. In the United Kingdom, the crown condition of the beech was worse on poorly drained, acidic soils. Healthy trees grew in soils with higher contents of base cations and low Al/Ca ratios. In beech forests on acidic sites in northern Germany, premature yellowing was accompanied by deficiencies of K and Mg. In France, damage to beech was found mainly at sites with low water reserves and on hydromorphic soils. At sites with intermittent water supply, wet periods can induce root rot by *Phytophthora* species, which makes the trees more susceptible to drought. This can cause a long-term reduction of vigour or even acute decline. Drought is seen as the main climatic factor having caused damage to the beech in the United Kingdom, Germany and Italy, probably aggravated by O_3. In these cases, long-term stress or severe stress events in the past, leading to chronic destabilization of the whole tree, rather than acute stress is stated to be the cause for the observed decline.

3. Biotic factors

(a) Insects

35. Various studies brought evidence that, mainly in eastern and central Europe, defoliation by insects played a predominant role in the outbreaks of oak decline. Defoliation in 2 or more consecutive years rather than one defoliation event is thought to be a primary causal factor. The most important insects are *Operophthera brumata, Tortrix viridana* and, except in cooler regions, *Lymantria dispar.* Repeated defoliation can lead to a lack of latewood formation, which can impair water transport to the shoot. Additionally, severe defoliation can result in a reduced root formation, which also renders the tree more susceptible to drought. For northwestern Germany, it is hypothesized that root damage due to waterlogging in 2 consecutive years was the predisposing factor for the recent decline of *Q. robur*, after severe defoliation by insects. The bark beetle *Agrilus biguttatus* Fabr. was found to be one of the earliest and most important secondary organisms.

36. Beech trees with increased foliar N/P ratio were more susceptible to attack by the leaf aphid *Phyllaphis fagi,* but leaf-eating insects do not seem to play a decisive role in the beech damage complex. From Germany and Switzerland, impairment of tree vigour resulting from bark necrosis caused by beech scale *(Cryptococcus fagisuga)* has been reported. The impact of the insect on the tree is intensified by a mild winter and high spring temperatures and aggravated by drought stress in early summer.

(b) Fungi and micro-organisms

37. Fungi of the genus *Phytophthora,* which cause root rot, were frequently discussed in the context of oak decline. In the Mediterranean region,*P. cinnamomi* is, in combination with drought, considered responsible for the decline of *Q. suber* and *Q. ilex. Phytophthora* species were also isolated from oak stands in warmer regions of central and eastern Europe, but it is doubted that they are of major importance for oak decline in central Europe. In this region it is more likely that oaks must be predisposed by other factors (i.e. excess N, impaired water supply, climatic extremes) to be severely damaged by *Phytophthora.* Predisposition by soil or climatic factors is also a prerequisite for the damage resulting from colonization by the various *Armillaria* species. Recently, evidence was provided that, in central Europe, *Phytophthora* is virulent especially in weakly acidic soils. In easternand southern Europe, *Biscogniauxia mediterranea,* which causes stem canker, has been associated with severe damage mainly of *Q. cerris* and *Q. frainetto,* probably due to predisposing drought stress.

38. Investigations on the mycorrhiza of declining oaks are scarce. In a Polish study, *Q. robur* with more severe symptoms of decline showed lower mycorrhizal colonization. In severely defoliated stands located in the Czech Republic, the percentage of active mycorrhizal root tips was negatively correlated with the degree of defoliation. However, the role of mycorrhiza in the oak decline complex is far from being understood. Some authors gave evidence for the participation of mycoplasma-like organisms, but this could not be confirmed by others.

39. In central Europe, *Phytophthora* species were detected in roots of declining beech trees and are thought, in combination with abiotic factors, to cause severe damage. Beech decline in Sicily was attributed to*Biscogniauxia nummularia,* which causes stem canker in trees predisposed by drought stress. Damage to shoots caused by *Nectria ditissima* is increased by high foliar N/K ratios. In a Czech and a British study, trees with poor crown condition showed significantly reduced fractions of live mycorrhizal roots. For the Czech stands, an impairment of the mycorrhiza by air pollution is assumed.

4. Silvicultural practices

40. In central Europe, no evidence for a significant contribution of mismanagement to the actual oak damage has been found. In France, however, the expansion of *Q. robur* into unsuitable sites may have rendered this species more susceptible to stress and thus contributed to the damage in the past

decades. In southern Europe, improper tending and overexploitation were found to be important predisposing factors for damage to the oak. In the area of the former Soviet Union, overmaturity of coppices predisposed oak to stress caused by climatic extremes and pathogens.

IV. EFFECTS ON SOILS

A. Introduction

41. Soils play an essential role in the water and element cycle of forests. Of prominent importance are the functions of soils for the whole ecosystem: the regulation of nutrient cycles and the filtering and buffering capacity is of great importance and, for example, indispensable for clean drinking water. Therefore, damage of soils and impairment of soil functions is always combined with an impairment of the whole ecosystem.

B. Soil degradation in Europe

42. All processes in soils depend strongly on the acid/base-status. The ability to maintain a certain pH range, the buffer capacity, is extremely important. An indication of soil acidification can be a decrease in soil pH, indicating the actual acidity, which is, however, partly influenced by seasonal processes. For the assessment of soil acidification processes the measurement of capacity factors is more reliable. Acidification means an increase in the exchange acidity (M_a cations: H^+, Al^{3+}, Fe^{2+}, Mn^{2+}) and a reduction in exchangeable `bases´ (M_b cations: Na^+, K^+, Ca^{2+}, Mg^{2+}).

43. Recently enhanced soil acidification has been proven by resampling forest soils at intervals of several years or even decades. Long-term chemical changes of forest soils have been reported from northern and central Europe since the early 80s. In Sweden several studies revealed long-term pH decreases in forest soils. Comparisons of sites in southern Sweden, receiving an estimated wet deposition of 0.45-0.55 kmol H^+.ha^{-1} (1985), with a site in north-central Sweden with an estimated deposition of 0.20-0.25 kmol H^+.ha^{-1} showed clear differences in the pH of the subsoil, which were explained by the difference in the deposition load. Sometimes even mineralogical changes were reported, which may counteract a complete reversibility of the current soil acidification. In Scotland, soil samples from 1949/50, resampled in 1987, showed decreases in pH, base cations, base saturation and cation exchange capacity, whereas extractable Al increased.

44. These changes are seen as a result of biomass accumulation, natural pedogenic processes and atmospheric pollution effects. At Rothamstead (United Kingdom), it was possible to compare pH values of soils over a period of 100 years. Under grassland, the pH_{H_2O} in the humus layer dropped from 5.7 (1863) to 5.1 (1984), under deciduous woodland from 6.0 (0-23 cm) and 7.0 (46-69 cm) around 1900 to 4.0 and 5.7, respectively, in the 1980s. In Germany studies in different regions were carried out dealing with this question, showing always consistent soil pH decreases or reductions in base cation contents (Westphalia, Hamburg, Berlin, Solling area in Lower Saxony, Black Forest, Bavaria). Data show a significantly greater base cation loss under conifers,

compared to broadleaved trees, which is the result of the higher deposition load due to the greater aerosol-trapping capacity in the evergreen canopy. Significant pH decrease in forest soils has been reported from various sites in Austria, but also from the southern Swiss Alps (due to the atmospheric depositions from Milan). Whereas soil acidification phenomena are measured all over northern and central Europe, similar results from southern Europe are missing.

45. Even if acid deposition decreases, recovering from soil acidification becomes difficult when the portion of exchangeable bases in soils reaches a level where the selectivity for base cations is very low. This aggravates the reversibility by natural processes.

46. Reduced buffering capacity of acidified soils can result in transport of acidity to ground and surface water. Fresh water acidification has been observed in many parts of Europe within the past 20 years. In Scandinavia large-scale acidification of lakes took place between 1950 and 1980.

47. Apart from obvious decreases in pH or base cation losses, various indirect effects in soils can give hints on actual or already passed soil acidification processes:

(a) A survey of beech stemflow areas in Europe (sites in Spain, Italy, Greece, Hungary) showed that the phenomenon of trunk base acidification could not be detected in Southern Europe, leading to the conclusion that the phenomenon seems to be restricted to central European regions affected by higher pollution loads;

(b) Between pH 5.0-4.0 Mn oxides - if available - are dissolved and often excess Mn is found in soil and leaves/needles. Unusually high Mn contents were found in sites in Germany, e.g. the northern Black Forest, the Eifel area, and in Hesse, often correlated with tree damage. Similar findings were reported from southern Sweden for beech, where high Mn concentrations were correlated with low Mg and Ca contents in the leaves. High Mn concentrations in needles/leaves thus indicate acid soil conditions;

(c) Discrepancies between chemical soil data (pH, C/N ratio) and those expected from profile morphology were identified in some European regions. They indicate an obviously great impact of external influences. In Baden-Württemberg (Germany), the results of the soil survey show that in A_h horizons without podzolizing features, where pH was expected to be around 5.0, the measured values were <4.2; at the same time the C/N ratio of the humus layers has decreased considerably in the past decades. The general tendency of C/N ratios to level out can also be seen in other regions in Europe;

(d) Soil fauna influences the physical soil structure to a large extent, e.g. by creating pore systems, producing clay-humus complexes, and decomposing organic material. Normally a great variety of species can be found, but acidification leads to a reduction in species abundance and amount of individuals. Reduced macropore volume due to reduced bioturbation was identified for upper mineral soil layers of the Solling area, Germany;

(e) The species composition of herb layers in forests show an increase in the number of acidophilic plants, but also nitrophilic vegetation, indicating acidification and eutrophication.

1. Soil degradation resulting from historical land use

48. Being the only energy source available in the past, the excessive consumption of wood for smelters, glass production, mining or as construction material led to large clear-felled areas in Europe. Often the original beech forest was successively replaced by spruces. Many European forests have experienced dramatic changes due to nutrient depletion resulting from excessive biomass harvesting in the past. In some European regions litter raking was practised until the 1950s and pasture in forests is still common practice. The essential difference between nutrient depletion due to historical land use is that historic nutrient depletion includes N (it is a “harmonic” pauperization), whereas the present-day pollution is combined with high N input, leading to nutritional disorders.

2. Interactions between plant and soil

49. Acidification / eutrophication of soils may lead to disturbance of tree nutrition in different ways: (i) the rooting system and mycorrhizae can be impaired; (ii) nutritional elements can become deficient; (iii) the supply of nutrients can be imbalanced; (iv) toxic concentrations of elements can occur; and (v) a spatial decoupling of demand and supply can lead to nutrient losses.

50. In soils, pH and the concentration of other elements strongly affect the toxicity of metal ions, e.g. Al. Below a pH of 4.2 and ca. 20% base saturation, Al^{3+} is present in soil solution, which is potentially toxic to fine roots, and Al restricts the uptake of Ca and Mg. Therefore, the Ca/Al ratio in soil solution can be used as indicator for acid stress. As a consequence, the rooting system of trees on many sites has become shallower over the past decades. This leads to a further decrease in spatial availability of nutrients and water.

51. The risk of Mg, Ca and K deficiency increases at sites with high N deposition. Especially excess NH_4^+ inhibits uptake of K and the NH_4/K ratio is used to assess the risk of nutrient imbalances. The risk of high NH_4^+ concentrations is highest in very acid upper soil layers, which reduce the capacity for nitrification. These soil conditions are widespread in central Europe. As NH_4^+ is preferred by most forest trees, root density increases in the upper horizons, leading to a flat rooting system, unbalanced tree nutrition and increased drought susceptibility. Both acidification and N excess thus lead to the same phenomena destabilizing forest ecosystems.

C. Effects of nitrogen

1. Introduction

52. The N input to the soil from throughfall in many European experimental sites is up to 60 kg N. The NO_3 fraction of the input is almost below 15 kg N, indicating that high input sites are dominated by NH_4 input. There is evidence that elevated N input increases N concentrations in foliage and litter, which increase the input to the soil and accelerate the internal N cycling. Nitrogen availability in the soil thus increases both directly from deposition input and by stimulation of N mineralization.

2. Nitrogen retention and nitrate leaching

53. Forest soils may have a high potential for N retention. However, compilations of input-output budgets have shown that above a threshold of some 10 kg N ha^{-1} yr^{-1} in throughfall NO_3 leaching (>5 kg N ha^{-1} yr^{-1}) occurred at many sites, and retention decreased with increasing proportion of NO_3 in deposition. Detailed process studies and experiments (N addition or N removal) at sites within the NITREX (Nitrogen saturation experiments) network showed that variability in NO_3 leaching could be explained by differences in 'N status'. Recent analyses suggest that forest floor C/N ratio is a good indicator for N status at least for coniferous forests and a relationship between C/N ratio and NO_3 leaching is found. Currently, forest floor C/N ratios may be used to assess risk for NO_3 leaching using >30, 25 to 30, and <25 to separate low, moderate, and high NO_3 leaching risk, respectively.

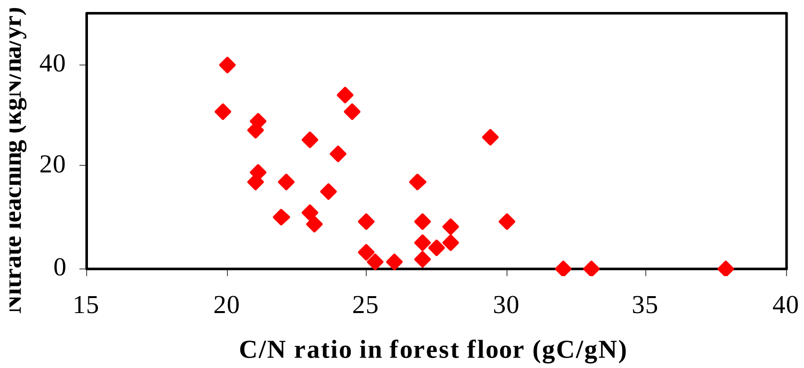

Figure 1. Nitrate leaching versus C/N ratio at 31 temperate forest sites in Europe (Gundersen et al., 1998a)

54. In the European Forest soil inventory approximately 40% of the sites had forest floor C/N ratios below 25. An important mechanism behind the shift of the balance between retention and leaching seems to be the onset of nitrification at forest floor C/N ratios around 24-27 or possibly a disruption of NO_3 immobilization at low C/N ratios. Declines in C/N ratio over time have been observed and lower C/N ratios coincide with areas of elevated N

deposition. The acidification potential from N input and N accumulation is released when NO_3 is leached. One kmol H^+ is produced for each 14 kg NO_3-N ha^{-1} yr^{-1} leached, and base cations and/or Al will be leached with the NO_3. The build-up of NO_3 from nitrification is largely regulated by climatic fluctuation, so that in N-saturated acid soils episodic events with Al concentration well above toxic limits may occur.

3. Effects on trees

55. Decline symptoms in European forests have often been connected to nutrient deficiencies. Nutritional imbalances have been documented near local sources of NH_3. It may be discussed if these effects are mainly related to direct uptake of especially NH_3/NH_4 in the canopy or if they are related to increased N availability in the soil. Experiments reveal that these effects mainly occur through the soil.

56. Possible mechanisms involved in the effects of excess N availability in soils on tree nutrition may be a combination of (i) nutrient losses due to NO_3 leaching and acidification; (ii) impairment of root growth; and (iii) ion competition in root uptake (NH_4 vs. Mg, Ca, K). Deficiencies of Mg or K are reported from several sites. Fine root biomass in coniferous stands decreased over the deposition gradient of the NITREX sites and with increasing N availability. Roof experiments have indicated improvements in root growth already after a few years of reduced N inputs.

57. Observations of increased tree growth in European forests over the past decades may be viewed as a contradiction to the potential negative effect of increased N input, although this is only one of several reasons that may explain this response. The question is if European forest can still respond to N. It was shown that there is a threshold for growth response of conifers at ca. 1.4-1.6% N in the needles, which correspond to the level where excess N is accumulated in the needles as arginine. Above the same threshold increased NO_3 leaching was found; the same sites have forest floor C/N ratios below 25-28. If these thresholds for N saturation are extrapolated to the whole of Europe by use of the ICP Forest soil inventory, some 40% of the forest will appear N-saturated at least if N deposition exceeds 10 kg N ha^{-1} yr^{-1}.

4. Effects on soil biology

58. A decline in the number of mycorrhizal species on roots was observed in a N pollution gradient; other studies show the negative effect of N on mycorrhizal fruit body production. Other changes in the microbial community may occur. Certainly, the above-mentioned increase in nitrification rate at organic layer C/N ratios below 24-27 is related to responses of the microbial community, which need further clarification.

D. Impact of heavy metals on forest ecosystems

1. Introduction

59. Quantifying the effects of pollutants is complicated, since responses to pollution vary with plant species and genotype, the responses measured and the developmental stages, further the dosage, types and combinations of pollutants, environmental regimes, and interactions of pollutants with plant diseases and insects. Effects caused by the exposure of organisms to heavy metal deposition may be related either to current deposition rates or to accumulated amounts in the ecosystem, some effects certainly being related to both. Metal uptake by plants plays the key role in the entry of metals to terrestrial food chains, because vegetation is foraged by herbivores or by detritivores. When plants accumulate metals, these metals can be ingested by animals thus creating the potential for toxic effects at higher trophic levels.

2. Mechanisms of toxicity and protection

60. Metal toxicity seems to be ascribable to interactions with enzymes, structural changes of cell membranes and P allocation. Thus, toxic metal concentrations in plants may be expressed rather indirectly in physiological dysfunctions affecting for instance root growth, transpiration as well as gain and allocation of carbon. Organisms exposed to elevated metal levels may react avoiding metal stress or by developing tolerance by various means, comprising (i) excluding heavy metals from uptake via active changes in rhizosphere chemistry; (ii) binding of metals at the inner surfaces of mycorrhizae and root cell walls; (iii) detoxification by special chelating agents or by carbonic acid complexes; (iv) occludation in external hyphae of mycorrhizae or in the root apoplast; and (v) distribution via xylem or maybe even phloem transport to storage locations and/or to excretion. Direct adsorption of deposited heavy metals to leaves/needles is negligible for Cd, low for Zn and strong for Pb.

3. Heavy metals in the soil

61. The plant-available pool of metals consists of (i) metal ions in soil solution; and (ii) metal ions bound on charged soil colloids, i.e. the exchange complex. The portion of plant-available heavy metals depends upon soil conditions such as (i) pH, (ii) redox potential, and (iii) amount and type of clays and organic matter. In general, availability of metals in soil increases with decreasing pH. Since only metals in their ionic form are taken up by plants, the speciation between ionic and complexed forms is crucial for toxicological risk assessments.

4. Risk assessment and thresholds

62. The lowest reported effect level was reached at: 20Fg L^{-1} Cd, 20-30 Fg L^{-1} Cu, 100-200 Fg L^{-1} Pb and 200-300 Fg L^{-1} Zn. Toxic Pb concentrations (. 20 Fg L^{-1}) have been exceeded in soil solutions of both humus and upper mineral soils in central European spruce forests (Solling, Harz Mountains),

which are know to be severely affected by long-range transported depositions. However, it has to be taken into account that in soil solution Pb, like Cr and Cu, is to a great extent present as metal-organic complex, known to be less toxic. Zn (650 Fg L^{-1}) and Cd (112 Fg L^{-1}) threshold concentrations have not been reached in field studies so far. Field data of soil solution concentrations for Hg and CH_3Hg are lacking, so that toxicity thresholds [2 Fg Hg L^{-1}; 0.2 Fg MeHg L^{-1}] are not assessable. On average, at equimolar concentrations, the relative toxicity of metals in culture solution decreases in the order: CH_3Hg > Hg > Cd > Cu > Pb > Zn. In comparison to spruce, threshold studies for beech (*Fagus sylvatica* L.) indicate minor susceptibility to heavy metals.

5. Mycorrhizae

63. As the roots of most plants are almost entirely mycorrhizal and mycorrhizae are the primary absorbing organs, possible effects of mycorrhizae on plant growth and metal tolerance is a question of increasing concern. Mycorrhizal capacity for metal uptake or exclusion and tolerance to metals vary greatly between species and even between strains of the same species and the metal considered. Heavy metals may exhibit effects on mycorrhizal fungi and on the interaction between fungi and plants, leading to nutrient deficiencies and other problems such as root disease and drought stress. Mycorrhizal fungi may be sensitive to increased levels of heavy metals. High levels of metals sometimes, but not always, decrease the level of mycorrhizal infection in plant, which in turn may or may not enhance metal uptake in the roots. Many studies confirm that some mycorrhizal fungi have a large capacity for protecting host plants from excessive metal uptake; some authors found that mycorrhizae enhance metal uptake at low soil metal levels, but protect plants from excess uptake at high levels.

64. It has been suggested that metal exclusion activity is generally stronger in mycorrhizal types which develop large fungal biomass than those which do not. Consequently, VA-mycorrhizae-forming herbaceous plants and deciduous trees would generally be more sensitive to metal contamination than conifers and their more metal-tolerant ectomycorrhizae. However, it could not be excluded that heavy metal pollution poses a selective force even on the ectomycorrhizae, leading to decreases in species diversity. This may in turn impair ecosystem elasticity.

65. The effects of heavy metals vary greatly between different types of mycorrhizae. Mycorrhizal infection may even be inhibited at soil concentrations of 45 mg Zn kg^{1} and 19-34 mg Cu kg^{-1}. To a certain extent mycorrhiza and root surfaces are capable of discriminating toxic metals (Cd, Cr, Pb), whereas essential elements such as Zn and Cu are often favoured. If metals are taken up by trees they are largely stored in roots and stems. Some woody plants may accumulate metals without exhibiting toxic effects. Such accumulators include *Sambucus*, *Vaccinium* spp., and *Populus tremula*, a plant that is foraged by moose and deer.

6. Soil micro-organisms and related processes

66. The decomposer communities play a crucial role within the natural nutrient cycles of forests, and they are strongly exposed to accumulated heavy metals in the top soils. This is the case for the so-called „organophile heavy metals“ Cr, Pb, Hg and slightly less for Cu, which is mostly bound to low-molecular substances. Processes that might be affected are (i) litter decomposition; (ii) C and N mineralization; and (iii) enzyme activity. However, it is difficult to estimate toxicity levels for microbially mediated processes and decomposer communities, due to differing soil properties and methodological discrepancies in the studies. Statistically significant activity depressions (20-40%) were measured when the heavy metal concentrations were 2-10 times higher than baseline samples, with the N transformation being the most susceptible process.

67. Adverse effects on soil-biological processes can be expected - according to the LOEL-concept (LOEL = lowest concentration for measurable adverse effects) - at concentrations of (in kg humus dry weight): 20 mg Cu, >30 mg Cr, 3.5 mg Cd, 0.75 mg Hg, 500 mg Pb. Although adverse effects on microbes are more difficult to assess, depressions certainly reflect changes in the functioning of decomposer biocenosis.

7. Soil mesofauna

68. Three main biological factors control metal accumulation in different groups of terrestrial invertebrates: (i) the diet; (ii) the structure and physiology of the digestive system; and (iii) the mechanisms by which metals are stored. Consistently, it was found that Cd and Pb levels are a function of nourish-physiological attributes of each individual species rather than of the position within the foodweb alone. Whereas Pb levels in animal samples are often below those of their estimated diets, Cd was enriched by several species. However, a common effect of metal contamination in soil animal groups is a decrease in species diversity.

8. The European view

69. In 1998 for the first time heavy metal data on the European Level I Monitoring Network are available for the soil solid phase. The findings can be summarized as follows: the majority of plots having an organic layer with high Pb or Zn concentrations is found in the region with the highest deposition load. Soils which accumulate > 100 mg kg^{1} of Pb in the organic layer are commonly observed in central Europe. However, critical concentrations of Pb, Zn, and Cd are exceeded in less than 1% of the plots for which values have been reported. Exceedances of critical organic layer concentrations of Cr and especially Cu have been reported more frequently, in 9% and 19% of the plots, respectively.

70. In general, very little is known so far about humus and soil solution concentrations. Maybe in future results from intensive monitoring sites within the framework of the European level II programme will manage to close these gaps.