STUDIA FORESTALIA SUECICA

Nr 78 1970

The effect of fertilization on sulphur dioxide damage to conifers in industrial and built-up areas

Effekten av gödsling på svaveldioxidskadade barrträd i industri- och bostadsområden

by

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ABSTRACT

The influence of SO_2 on pine (*Pinus silvestris*) and spruce (*Picea abies*) has been studied as well in laboratory experiments with different doses of the gas and under different environmental conditions as in field experiments in some industrial districts and in a built-up area near Stockholm. The purpose of the investigation was to try to find out whether it is possible to improve the conditions of the trees by fertilizing so that the susceptibility to gas damages can be reduced. The fertilizers were N and NPK respectively. An evident tendency to recovery of the trees could be seen after fertilizing of stands that were continuously exposed to SO_2. Any recovery of the trees in shallow soils which had been fertilized with nitrogen could not be observed. In heavily SO_2-damaged stands one can very often find single trees not having been affected at all. Further experiments on genetic resistance in pine populations exposed to SO_2 are going on.

Ms. received 31 December 1969

ESSELTE TRYCK, STHLM 70

012036

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1. Introduction

Great attention has been paid in scientific literature to the effect of sulphur dioxide on vegetation, particularly in Central Europe, the U.S.A. and Canada. Different forms of vegetation show great differences in the degree of sensitivity to impurities in the air. It is, however, difficult to compile sensitivity tables for various species, and it is sometimes the case that individual specimens of one and the same species can show different degrees of sensitivity to impurities in the air.

Airborne impurities in the form of SO_2 are particularly common in various industrial districts and built-up areas. Lichens, which obtain all their nourishment from the air, have been studied with regard to sensitivity to SO_2 more than any other form of vegetation (cf. SKYE, 1958, 1965, 1968; LUNDSTRÖM, 1968; DE SLOOVER & LE BLANC, 1968). Certain species have shown themselves to be extremely sensitive and have consequently often been used as SO_2 indicators, not least for establishing the degree of pollution in and around industrial areas. Where higher vegetation is concerned, it would appear that conifers are among the more sensitive. An exception are such conifers as shed their needles each year, for instance larch.

SO_2 damage is more difficult to demonstrate than many other symptoms, caused for example by fumes with a fluorine content, as it is not possible to demonstrate them with absolute certainty with the help of microchemical analysis. This is because the SO_2 absorbed by leaf tissues is rapidly converted into sulphate, and is incorporated in the organic vegetable substance in the same way as the sulphur which the plant normally takes up as sulphate compounds through its roots.

The unfavourable effect that SO_2 has on plants is thought to depend in the first place on the circumstance that the gas infiltrates through the leaf stomata or clogs these, thereby affecting both the photosynthetic and transpiratory processes. Chlorophyll has been shown to be very sensitive to SO_2 in high concentrations. Frequently the damage does not affect the entire plant or tree but occurs locally. Damaged areas can never recover and resume normal development, although the unaffected areas function normally when no longer exposed to the fumes.

Forest damage due to industrial fumes has been the subject of particular attention in West Germany, Czechoslovakia and Austria, as also in the U.S.A. and Canada (cf. SCHRÖTER, 1908; STOKLASA, 1923; GUDE, 1954; ZIEGER, 1955, 1960; SCHEFFER & HEDGCOOK, 1955; REINHARDT, 1959; LAMPADIUS, 1960; a.o.). Even when the change-over from wood-firing to coal-firing occurred a certain injurious effect on the surrounding vegetation was noticed. This was particularly the case where conifers were concerned. Good resumés of earlier literature on this subject are given by THOMAS (1951), SIMONSSON (1956), PELZ (1958), WEDIN (1960), KELLER (1964), KÄMPFER (1966), WENTZEL (1966), KNABE (1966), DONAUBAUER (1966), WESTERGÅRD (1969), LUNDHOLM (1969) a.o. STÖCKHART showed as early as 1853 in his work at the Department of Forestry Plant Chemistry at Tharandt that SO_2 was the most active substance in smoke. A large number of tests, especially in the Central European industrial areas, have shown that SO_2 has been found to cause the commonest and, next to fluoride gas, the severest smoke damage to date (cf. ROMELL, 1941; WENTZEL, 1956; KARLÉN & TYDÉN 1958; ZIEGER, 1960; JAHNEL, 1962; VENN, 1966; KARLÉN, 1967; ODÉN, 1968). This has also been established in a large number of tests made in Canada and the U.S.A. from the early 1900's.

Only a very few tests appear to have been made as regards the possibility of taking steps to *prevent or reduce the effect of smoke damage to forest trees.* The following measures are feasible in principle:

1. The purification of gases with regard to poisonous emissions
2. The changing of tree species
3. Resistance breeding with emphasis on sensitivity to smoke damage
4. Influencing the external factors, which can reduce damage caused by flue gases.

In this paper the last-mentioned possibility will be illustrated by a series of experiments varying some of the pertinent environmental factors, more especially the condition of the trees as affected by different applications of growth nutrients. The test areas chosen were partly two industrial environments—the Kvarntorp-Hynneberg area in Närke and the Mo and Domsjö factory site in Domsjö, Ångermanland—and partly the town district of Lidingö, near Stockholm. Work in the Kvarntorp area was carried out during 1956 to 1959 and in Domsjö and the Lidingö district between 1967 and 1969. In the latter places the work was in part done in the form of examination work in forest botany at the Royal College of Forestry by BJÖRN ELFVING and SUNE SOHLBERG, now forest officers, several of whose observations are quoted below.

The chemical analyses were carried out according to standard methods used by the State Agricultural Chemical Laboratory in Uppsala.

The test was performed partly by making observations of smoke damage in the field, partly with experiments in the laboratory and in the open.

2. Survey of the external factors which can affect damage to trees caused by flue gases

2.1. The degree of concentration of the gas and the duration of gassing

The degree of concentration of the gas and the duration of the effects of it are naturally of great importance. Since different types of trees and even individual trees of the same species can differ considerably in their sensitivity to SO_2 damage, it is impossible to give a general demarcation value for such damage. In general terms, however, it is considered that the demarcation value can be put at about 5 mg SO_2 per m^3 of air, i.e. at 2 ppm (= 0.0002 per cent by volume). Great variations occur due to the influence of external factors however. Also the duration of fumigation affects trees in different ways under different external conditions. According to a report from the Kvarntorp industry, flue gases issuing from two 100 metre chimneys often had a total SO_2 content of approximately 0.7 per cent by volume at the actual point of exit. Simultaneously 0.005 – 0.008 % SO_3 and about 0.02 % H_2S were emitted. The amount of SO_2 emitted every 24 hours was given as roughly 200 tons. In addition about 1 g of "ash" per m^3 was said to be discharged. However, the amount of SO_2 was diluted very rapidly, and on one occasion the amount measured at ground level 250 m from the chimneys was 50 ppm, or 0.005 per cent by volume. On another occasion the content of SO_2 measured at different distances from the open furnaces at Hynneberg was 130 ppm at 200 m, 100 ppm at 400 m and 70 ppm at 600 m. The course taken by the gas is frequently very narrow and short, a circumstance, however, which can lead to concentrated damage, for instance of forests. In adjacent areas the SO_2 content can be under 1 to 2 ppm.

2.2. Temperature

According to American reports conifers are equally sensitive to SO_2 during growth as they are in the winter, and similar observations have been made in among other places the Kvarntorp area in Sweden. An explanation could be that, with the exception of the very coldest periods, the stomata are never completely closed in winter. Where larch and deciduous trees are concerned, damage from SO_2 during the winter has been found to be negligible in comparison to that sustained by evergreen trees. In favourable temperature conditions, when photosynthesis, respiration and transpiration are functioning normally, the degree of sensitivity to gas damage is greater. The gas does not interfere with the respiratory process, however, but makes a passive entry via the stomata in the same way as CO_2 and O_2 to the inner parts of the leaf (cf. KISSER, 1965).

2.3. Wind conditions

It has been known for a long time that damage to vegetation is distributed very unevenly in relation to the source of emission, and prevailing winds can lead to more extensive damage in the wind direction. Forest damage in the vicinity of the Kvarntorp shale workings is a typical case of such an eccentric damage pattern. Extensive examinations have been made in this area on several occasions, e.g. by the State Forest Research Institute in 1948 and 1953 and in 1958 (ÖSTLIN, 1959). As early as 1947 E. RONGE investigated the damage in this area with particular emphasis on the injurious effect to the forest nearest to the source of the gas. Since then he has carefully measured the effects of the smoke issuing from the open furnaces at Hynneberg, where Yxhult Stenhuggeri AB's plant also produced gases with an SO_2 content. These observations as well as observations by LIHNELL (1969; cf. PETERS, 1969) showed that the damage was most severe towards the north-east, that is to say in the same direction as the prevailing wind.

Similar tests have also been made in many other industrial countries, not least in Germany where tests were made in the 1800's in conjunction with the industrial breakthrough. Researchers in Austria and Czechoslovakia in particular have observed how the gas follows the valleys and the air currents, which very quickly carry the air up the surrounding slopes. The stratification of the air and the ways in which this is disturbed by the rising and setting of the sun during the vegetation season, as also the way in which SO_2 sinks to the ground at morning and night have been studied in among other places British Columbia. In Sweden, too, comprehensive observations have been made of the frequently localised damage to trees in the vicinity of industry, e.g. on the edge of forests or even in the middle of forest stands, as in Karlbergsparken near Köping. Damage of this nature must in every case depend on very limited currents, and in certain cases partly also direct downstreams, of air in the atmosphere. Moreover, everything suggests that also other toxic gases play a part in causing such damage (cf. LINZON, 1965 and SKYE, 1969).

2.4. Airborne particles

Airborne particles in the form of dust, lime, soot, etc. can have both a mechanical and chemical effect. In the first instance the leaf stomata are clogged, thereby interfering with the CO_2-exchange of the leaves or needles; in the second instance the gas dissolves in water on the surface of the needles, whereby its effect rapidly dissipates, particularly as SO_2 is then transformed into considerably more inert sulphates.

2.5. Light

Since the stomata opening is controlled by the light factor the most probable gas damage may occur in daylight.

2.6. Humidity

Under general good moisture conditions the stomata are normally open, thus allowing the gas to pass through them more easily. In accordance with this the damage from the SO_2 gas seems to be lesser under drier conditions, while melting snow on branches and needles entails an increase in the amount of damage.

Needless to say, the soil moisture has in principle the same effect as the humidity of the air. In this respect it has been established that conifers in damp sites with a plentiful water supply are more sensitive to flue gases than trees in drier sites. Judging from Czechoslovakian experiments (PELZ & MATERNA, 1964), soil moisture also appears to be of great importance with regard to the effect which fertilization can have on resistance to flue gases.

2.7. Nutrient supply

The effect of the soil's nutrient supply and fertilization on sensitivity to smoke damage has long been the subject of study (cf. KELLER, 1958; WENTZEL, 1959; THEMLITZ, 1960; MATERNA, 1964; ROHMEDER & VON SCHÖNBORN, 1965; ZUNDEL, 1965). Protracted observations in different damage areas have indicated that numerous cultivated plants have become more resistant after fertilization. In this way, for instance, ZAHN (1963) demonstrated that rape which had been fertilized in various ways was much more able to withstand SO_2 fumigation than were plants which had not been fertilized. Everything indicated that it was nitrogen (120 kg N per hectare) that had the best effect, and that the strengthening of the condition of the plants played a decisive role. Also corn showed a better resistance to SO_2 after fertilization, although not so clearly as in the case of rape.

Such a univocal result has not been obtained in the case of forest trees as for several agricultural plants. Thus MATERNA (1962), when making fertilization experiments in a spruce stand which had been damaged by smoke, was unable to find any increase in resistance after applying plant nutrients, even though an increase in growth could be established. LAMPADIUS & HÄUSSLER (1962), however, considered that they could establish improved resistance to SO_2 after fertilization. PELZ (1962) discovered that both the percentage of dead trees and signs of smoke damage increased in a spruce stand with increased productivity and site water supply. He attributes this to the higher turgor of the leaf cells, and increased photosynthetic activity and open stomata, which gives the gas free passage.

In an experiment using spruce germinal shoots, raised in normal arable land mixed with compost to which had been added nitrate and phosphate (5 g Nitrophoska per pot), ROHMEDER (1960) found that when they were exposed to varying amounts of SO_2 and HF, only 30 per cent of the fertilized plants were damaged compared with 95 per cent in the case of the control plants. In other tests he also used an admixture of lime, but this did not result in increased resistance. This was assumed to depend on the relatively high lime content of the subsoil.

2.8. The resistance of different specimens

It has been mentioned already that in many places and different tests it has been noticed that a natural and presumably hereditary resistance exists in different specimens of the same population. Such observations have been made not least in the case of conifers, for which reason breeding work aiming at the isolating of resistant clones or specimens can be regarded as worthwhile (cf. PELZ, 1956; von SCHÖNBORN, 1963 and SCHÖNBACH a.o., 1965). However, at lot of time would have to be devoted to such work before any practical results could be expected (cf. HEPTING, 1968).

The precaution which at the moment seems to be most encouraging, and which offers a way of successfully combatting smoke damage in the short term without changing the actual source of emission, is to endeavour to strengthen the condition of the trees and improve their resistance with the help of fertilization. This paper is consequently devoted to this problem as it concerns pine and spruce and describes various fertilization tests in the field. Certain laboratory tests using pine, spruce and alder plants were also conducted with a view to obtaining information on the significance of individual environmental factors.

3. Laboratory tests using pine, spruce and alder plants exposed to SO_2 fumes

3.1. Materials and methods

3.1.1 Material

The test material consisted of 2+0 pine (*Pinus silvestris* L.) and spruce (*Picea abies* Karst.) plants and 1+0 alder (*Alnus glutinosa* L.) plants raised in a greenhouse. Pine plants were used only in preparatory tests, at which time it was noticed that spruce plants were much more sensitive to SO_2 fumes. For this reason spruce plants were used in the main experiments as test material. Alder plants were used in only one experiment to provide a comparison.

3.1.2 Test cabinets

These consisted of specially constructed, gas-tight containers measuring 70 × 70 × 60 cm and with a volume of about 300 l. One side could be opened, but was fitted with gas-tight sealing strips which sealed with the help of screw clamps when tests were in progress (Fig. 1). The test cabinets also had a gas-tight opening in the upper part for the admittance of gas, a similarly gas-tight hole in the lower part for the cable to the electric fans inside the cabinets, and tubes for ventilating the cabinets. The tops of the test cabinets were in the form of troughs, which could be filled with water when the plants were being subjected to radiation from above the cabinets by fluorescent tubes (6000 lux). The heat generated by the tubes was effectively eliminated by this water filter.

3.1.3 Cultivation vessels

Ordinary clay pots in which the plants were set in soil were used in the preparatory experiments. As the introduced gas was found to be absorbed and quickly dissolved in the soil moisture (to H_2SO_4), it was not possible to retain a sufficiently high gas concentration in the air for any length of time. The method was therefore modified in various ways, including covering the soil in the pots with Al-foil. As this did not lead to a satisfactory result the method of planting in soil was discontinued.

Erlenmeyer flasks with a volume of 300 ml and containing various nutrient solutions were used instead. By using a special device it was possible to expose

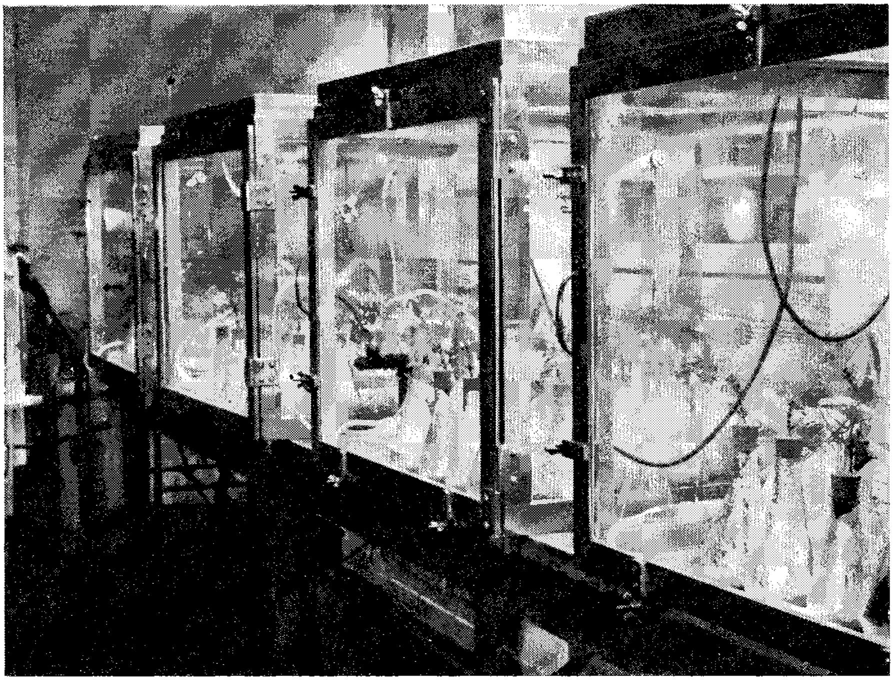

Fig. 1. Gas-tight glass cabinet for testing resistance against SO_2.

the green parts of the plants freely to the air, while their roots were submerged in the solution. With the help of a specially arranged and gas-tight tubing system leading through the rubber stoppers in the flasks, a continuous supply of air could be kept gently bubbling through the solution. To prevent condensation and the formation of drops of water in which the gas could dissolve, each cabinet was fitted with a fan, partly covered with Al-foil (see Fig. 2), which was switched on for 1 hour out of 24.

3.1.4 Gas supply

SO_2 was introduced into the cabinets from an ordinary SO_2 tube which was fitted with a specially constructed valve system. This apparatus made it possible to introduce controlled amounts of gas into the test cabinets (Fig. 1). The same amount of gas was introduced at the same time every other day during each separate test. SO_2 was introduced into the test cabinets in three different amounts during each experiment in three of the four cabinets. No gas was introduced into the fourth cabinet, and the plants in it were used as control material.

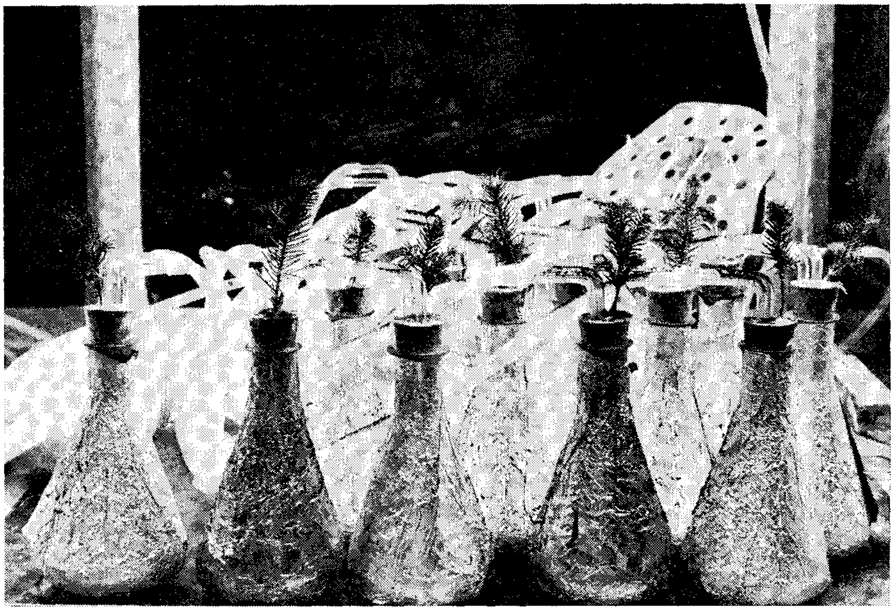

Fig. 2. Part of the test equipment with spruce plants in sealed Erlenmeyer flasks with a supply of air to the roots at varying quantities of SO_2 in the cabinet.

To determine the most suitable amounts of SO_2 to use, many preliminary tests were made (cf. MÜHLSTEPH, 1942; HÄRTEL, 1953, 1958, 1960; PELZ, 1958, 1959; BEATON, BURNS & PLATOU, 1968). At the same time a study was made of the length of time during which a constant gas concentration could be maintained. The amount of SO_2 in the air was measured with a Dräger-Gasspürgerät, Mark 19/31, which gave good values. Immediately after the introduction of a known quantity of gas, this apparatus gave a reading which agreed well with the actual amount of gas introduced into the cabinet. This method could consequently be used to follow the changes in the SO_2 concentrations in the cabinets during the experiments by tapping off small quantities of air through the holes in the sides of the test cabinets.

3.1.5 Tested SO_2 quantities

It has already been mentioned that an SO_2 concentration of about 2 ppm is the approximately critical value where damage to conifers is concerned. On the other hand it has been considered necessary to investigate the effects of the low SO_2 concentrations which occur in the atmosphere in the vicinity of industrial emissions. As the gas concentrations used in the laboratory tests ought to be compatible with those occurring under field conditions, it follows that concentrations exceeding 100 ppm should have been tried. Preliminary experiments showed, however, that a concentration of this magnitude led to the immediate withering of the plants. Moreover, sustained gas concentrations of this order seldom occur in natural circumstances. The experiments therefore used concentrations of between 3 and 70 ppm. Also lower values were tested, but the damage sustained during tests with these amounts could not be discerned for such a long time that the plants, affected as they were by the artificial test milieu, could no longer be regarded as reliable test material.

3.1.6 Variations in the gas concentration during the tests

It was clearly established during the experiments that the amount of gas introduced into the cabinets decreased very considerably, due no doubt to the SO_2 being absorbed by the plants or converted into sulphuric acid; in completely empty cabinets into which a similar amount of gas was introduced the amount of SO_2 could be kept much more stable. Thus it was not possible with the available test equipment to test the effect of SO_2 in a stable concentration. Experiments of this nature call for a continuously percolating supply of gas, which is only possible with considerably more sophisticated equipment than was available. Since in actual field conditions emissions of gas of rather short duration and in a definite direction are much more common than a constant flow of gas, it was considered that the test method employed, consisting as it did of regular and time-controlled emissions, would reflect natural conditions in a more acceptable way.

The gas was therefore admitted every other day and the concentration was continually checked with the help of air samples. As a rule the experiments lasted one month.

3.1.7 Solid particles on the test plants

To examine the effects of solid particles in the atmosphere, e.g. in the form of ash issuing from chimneys in industrial and built-up areas, use was made partly of active carbon, and partly of ash obtained from the chimneys in Kvarntorp and the open furnaces in Hynneberg.

3.1.8 Illumination

The source of light, fluorescent tubes in a 50×60 cm ramp, gave a total output of approx. 6000 lux on the top of the test cabinets. All experiments were conducted with illumination for 18 hours and darkness for 6 hours each day.

3.1.9 Recording gas damage

The extent of the damage caused by SO_2 was recorded as the percentage of damaged and dead needles or leaves of the correspondent total number for each plant. Thus 0 indicates completely healthy plants, 50 that half of the leaves (needles) were brown or affected by SO_2, and 100 that the plants had perished or were dying.

3.2. Experiment 1. The effect of different concentrations of SO_2 on spruce and alder plants

The experiment used 2 + 0 spruce plants and 1 + 0 alder plants reared in greenhouses at the College of Forestry. The plants were put in 300 ml Erlenmeyer flasks through the rubber stoppers which had been sealed off with gastight material (degras and vaseline). The nutrient solution had the following composition:

NH_4NO_3	856 mg/l distilled water
H_3PO_4	1600 ,, ,, ,,
KCl	1220 ,, ,, ,,
$CaCl_2$	2020 ,, ,, ,,
$MgSO_4+7H_2O$	3000 ,, ,, ,,
Ferricitrate	33 ,, ,, ,,

Ordinary firewood ash was scattered as evenly as possible over the plants. SO_2 was introduced every other day in concentrations of 5, 10 and 20 ppm. The experiment was terminated after 18 days.

The outcome of the experiment is given in Table 1. Table 1 shows that all the plants withered faster in higher gas concentrations than lower, and that the alder plants were more sensitive than the spruce plants to SO_2. Plants covered with ash, which is able to absorb the gas, were much more sensitive than plants without ash.

3.3. Experiment 2. The effect on spruce plants of SO_2-saturated active carbon at different temperatures

The experiment used 2 + 0 spruce plants placed in 300 ml Erlenmeyer flasks as in Experiment 1. Before the flasks were put into the test cabinets the needles of the plants were powdered as uniformly as possible with active carbon which had been saturated with SO_2 at temperatures of 20°, 100° and 200°C. Considerably more SO_2 can be absorbed by the coal at low temperature. The outcome of the experiment is given in Table 2.

Table 1. Percentage damaged needles from 2 + 0 spruce plants and 1 + 0 alder plants kept in aerated nutrient solution in glass flasks placed in gas-tight glass cabinets with various SO_2 concentrations. Plants partially strewn with wood-ash. Duration of experiment 18 days.

After no. of days	Without SO_2 (control)				5 ppm SO_2				10 ppm SO_2				20 ppm SO_2			
	Spruce		Alder		Spruce		Alder		Spruce		Alder		Spruce		Alder	
	With ash	Without ash	With ash	Without ash	With ash	Without ash	With ash	Without ash	With ash	Without ash	With ash	Without ash	With ash	Without ash	With ash	Without ash
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0
6	0	0	0	0	0	0	2	0	0	0	20	5	15	5	60	20
9	0	0	0	0	1	0	7	0	2	1	60	5	40	15	70	40
12	0	0	0	0	2	0	8	2	5	2	70	5	50	20	85	50
15	0	0	0	0	4	0	10	4	5	5	75	5	60	25	90	60
18	0	0	0	0	10	5	20	4	15	5	80	10	65	30	95	65

Table 2. Percentage damaged needles from 2 + 0 spruce plants reared in nutrient solution in aerated glass flasks placed in gas-tight glass cabinets. Immediately prior to placing in test cabinets plants powdered with active carbon saturated with SO_2 at different temperatures. Duration of experiment 30 days.

After no. of days	Active carbon without SO_2	Active carbon saturated with SO_2 at		
		20°C	100°C	200°C
10	0	10	10	0
15	0	45	35	0
20	5	75	50	0
25	5	85	55	5
30	5	100	60	5

Table 2 shows that active carbon saturated with SO_2 at 20°C and brought into contact with the needles had a strongly injurious effect on the spruce plants. Signs of extreme damage to almost half of the plants could be seen after 15 days, and all the plants were dead after 30 days. Considerably less damage would have ensued had the carbon been saturated at 100° or 200°C.

It is also possible to conclude from this experiment that ash distributed in the air straight from kilns, where the temperature is high, should be less harmful to the surrounding vegetation than the SO_2 saturated ash from tall chimneys, where the temperature is usually lower. The accuracy of this conclusion has been confirmed with the help of comparative experiments.

3.4. Experiment 3. The effect of SO_2 in three different concentrations on spruce plants in various nutrient solutions

The experiment used 2 + 0 spruce plants in Erlenmeyer flasks with nutrient solution which was varied with regard to its content of nitrogen, phosphorous and potassium. This method, however, did not make it possible to obtain distinct differences in gas damage to the plants in the various solutions. The probable reason for this is that the unnatural conditions made it impossible for the plants to adjust themselves during the brief duration of the experiments in time for the differences in the needles' eventual susceptibility to gas damage to be noticed.

The effect of various nutrient applications was therefore tested in the field.

4. Field tests involving the fertilization of heavily damaged pine and spruce at Hynneberg in central Sweden

To make a detailed study of whether a strong but for growth normally advantageous dose of different nutrients could affect the degree of resistance of forest trees to SO_2, two series of fertilization tests were conducted at Hynneberg, where particularly pine *(Pinus silvestris)* and spruce *(Picea abies)* had sustained severe SO_2 damage.

4.1. Experiment 1. Mixed stands in rich soil

Fourteen 10 × 10 m sample plots intended for fertilization were arranged in a mixed stand of about 50 years 200 to 400 m from the nearest source of emission, viz. the open furnaces at Hynneberg. The ground vegetation was very irregular but consisted for the most part of grass (*Deschampsia flexuosa, Calamagrostis arundinacea, Poa pratensis, Agrostis* sp.) and herbs (*Anemone hepatica, Hypericum perforatum, Trientalis europaea, Luzula pilosa,* a.o.) and patches of twigs and bushes, more especially *Salix* species and *Rubus idaeus*.

Each plot was reproduced twice, and it was arranged that one of the test plots in each test combination was put in a more uniform part of the area with predominately 60 year-old pines. In Table 3 the various test combina-

Table 3. Chemical analyses of soil samples from differently fertilized test plots in test areas with SO_2 damaged pine and spruce forests near Hynneberg. Fertilization in May 1957 and soil samples collected for analysis August the same year.

Test plot	Fertilizer type	Kg per ha of N, P_2O_5 and K_2O respectively	Weight by volume	pH	Lactate value mg P_2O_5 per 100 g soil	Potassium value mg K_2O per 100 g soil	Nitrogen mg/100 g soil		
							Total N	NH_4–N	NO_3–N
O	—	—	1.2	5.6	1.1	5.3	221	0.9	0.1
N	$(NH_4)_2SO_4$	150	1.1	5.2	2.6	9.4	349	10.6	0.4
P	superphosphate	400	1.2	5.6	46.0	6.8	183	0.5	0.3
K	K_2SO_4	300	1.2	5.8	1.8	37.0	148	0.5	0.8
N + P	$(NH_4)_2SO_4$ + superphosphate	150 400	—	—	—	—	—	—	—
N + K	$(NH_4)_2SO_4$ + K_2SO_4	150 400	—	—	—	—	—	—	—
P + K	superphosphate + K_2SO_4	400 300	—	—	—	—	—	—	—
N + P + K	$(NH_4)_2SO_4$ + superphosphate + K_2SO_4	150 400 300	1.2	5.9	53.0	26.5	160	0.6	0.1

Table 4. Chemical analyses of annual needles from spruce collected in August 1958 from different test plots with SO_2 damaged pine and spruce fertilized in May 1957.

	mg per g dry substance				
Test plot	Total N	P	K	Ca	S
Experiment a					
Unfertilized	14.5	1.5	7.2	4.5	1.9
Fertilized with N	18.7	2.1	8.4	6.4	2.4
Fertilized with P	15.5	2.6	9.0	10.3	2.4
Fertilized with K	17.0	1.9	7.8	8.3	2.2
Fertilized with P+K	17.8	2.9	10.6	4.3	—
Fertilized with N+P+K	17.0	2.1	7.2	5.3	1.9
Experiment b					
Unfertilized	17.2	1.9	6.2	6.3	2.8
Fertilized with N	17.0	1.4	7.6	3.8	2.8
Fertilized with P	19.2	3.0	8.5	7.3	2.4
Fertilized with K	12.6	1.9	9.6	6.3	2.6
Fertilized with N+K	21.3	1.9	5.3	7.0	2.3
Fertilized with P+K	18.7	1.8	8.0	5.8	2.9
Fertilized with N+P+K	15.4	1.6	8.7	6.8	2.9

tions have been collocated with an indication of the amount of nutrient per hectare and with the analysis values of the humus layer (to a depth of 10 cm, fraction > 2 mm) of different test plots in the open section of the experimental field. The fertilizer was applied manually and as evenly as possible in May 1957. Soil samples were taken for analysis in August the same year.

Table 3 shows that the application of various nutrients usually left distinct traces in the soil on the respective test plots. In itself, however, the area cannot be regarded as being poor in nitrogen and mineral nutrients. It is of interest that the nitrogen is apparently consumed more completely if mineral nutrients are applied simultaneously.

Existing damage to trees and tree plants was carefully recorded before fertilization was carried out. When the first inventory was taken 4 months later the same trees were recorded and compared (by the same person) with the earlier record of damage. The same procedure was followed when the second inventory was taken in June the following year. The outcome of the test is not accounted for here in detail because of the fact that it was not possible to establish distinct differences in attack on the various test plots.

The negative outcome of the tests is probably due to some extent to the relatively good quality of the soil before treatment. The outcome of fertilization experiments in soil of good quality in south Germany made by ROHMEDER & SCHÖNBORN (1965) was similar to the above and was interpreted in the same way.

Table 5. Chemical analyses of soil samples from differently fertilized test plots in test areas with isolated SO_2 damaged spruce 1 km from Kvarntorp. Fertilization in May 1957 and soil samples for analysis collected in August the same year.

Test plot	Fertilizer type	Kg per ha of N, P_2O_5 and K_2O respectively	Weight by volume	pH	Lactate value mg P_2O_5 per 100 g soil	Potassium value mg K_2O per 100 g soil	Nitrogen mg N per 100 g soil		
							Total N	NH_4–N	NO_3–N
O	—	—	1.1	5.8	1.0	9.0	250	1.1	0.4
N	$(NH_4)_2SO_4$	150	1.0	5.8	1.0	8.0	440	9.8	0.7
P	superphosphate	400	1.2	5.9	1.0	10.0	180	1.0	0.3
NPK	$(NH_4)_2SO_4$ +	150							
	superphosphate +	400	1.0	6.0	1.1	15.0	260	1.2	0.6
	K_2SO_4	300							

Neither did chemical analyses of the needles taken from the various test plots (Table 4) provide any clear information. No influence on the S-content of the needles collected from trees which had been fertilized in different ways on the various plots could be discerned.

4.2. Experiment 2. Fertilization experiment on spruce in parkland

Test plots which were fertilized in various ways were arranged in a park 1 km outside Kvarntorp round individual 20 year-old spruce trees which were more or less badly damaged by SO_2. The same fertilizer and quantities per hectare were used in this case as in the previous experiment. The test plots were circular with a radius of 2 m and one tree in the centre. The fertilizer combinations used were repeated three times and are shown in Table 5. This table also contains a collocation of the results of soil analyses of the top layer (to a depth of 10 cm) of the various test plots.

This experiment showed, that, as in the previous test, no definite difference in resistance to SO_2 connected with the fertilization could be established, neither could any certain change in the sulphur content of the needles in relation to the nutrients applied be observed.

5. Fertilization test on severely smoke-damaged pine forest in Domsjö near Mo and Domsjö Company's factories, Örnsköldsvik

In collaboration with Mo and Domsjö Company a number of test plots were arranged in Domsjö roughly 1 km from the Alfredshem factories (Fig. 3). The purpose of this was to make it possible to study a larger area of forest on badly nourished ground which had been exposed to SO_2 damage. Statistics of the wind direction in this area were available, and the SO_2 content of the atmosphere was recorded in the immediate vicinity of the test plots (Fig. 4).

5.1. Description of the test plots

Test plots were laid out on dry and moist ground. Thus three plots were arranged on firm ground and two on marshland. The laying-out was performed by Björn Elfving and Sune Sohlberg – at that time students at the Royal College of Forestry – and ranger L. von Post of the Mo and Domsjö forest administration. On the plots on firm ground all stages of SO_2 effects were present among the older pines, while on the marshland plots the damage was somewhat less.

The test plots measured 30 × 50 m and were separated by 10 × 5 m strips. Plots I, II and III were all exposed to the west directly towards the sulphite factory in Alfredshem. Productivity was lower on the plots on dry land, where outcrops of rock were not uncommon.

The test plot vegetation consisted mainly of pine (*Pinus silvestris*) and small, non-growing spruce (*Picea abies*), as well as bush of birch (*Betula verrucosa*), alder (*Alnus incana*), mountain ash (*Sorbus aucuparia*) and species of *Salix*. Heather (*Calluna vulgaris*) dominated in patches, and here and there was interrupted by patches of *Vaccinium myrtillus* and *V. vitis idaea* and *Empetrum hermaphroditum*. There were no outcrops on plot II. The vegetation was dominated by pine with slowly growing spruce and hardwood shrubs. The heather was more abundant than on the other test plots. There were many patches of *Vaccinium myrtillus*. Approximately 5 % of test plot III consisted of visible rock. Here too pine dominated, with slowly growing spruce and hardwood shrubs of the same type as on test plot I. The remaining vegetation was also generally similar. *Lastraea dryopteris* and *Fragaria vesca* occurred in the south-west corner of the test plot. The two damper test plots IV and V both measured 40 × 40 m and were separated by a 10 × 40 m wide strip. The site quality was very uniform, although a moister section occupied the north-west corner.

Test plot I was fertilized with nitrogen in the form of lime ammonium

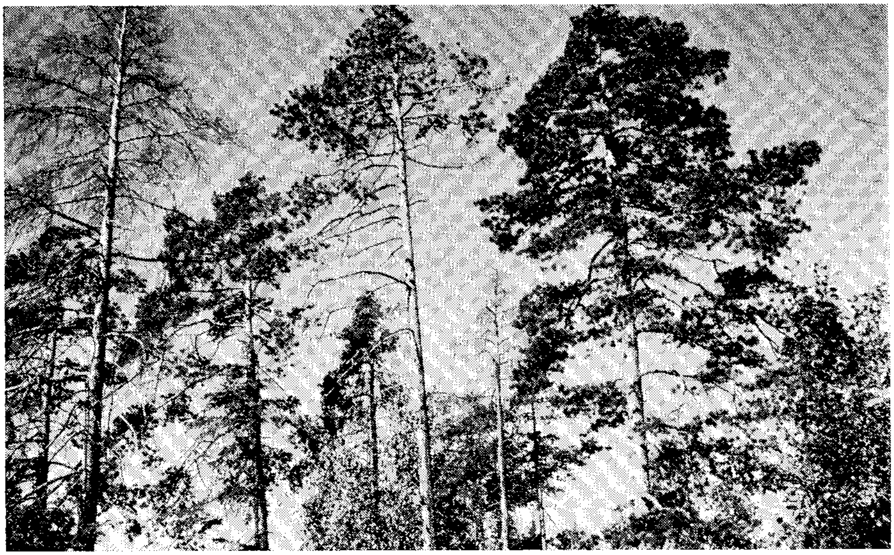

Fig. 3. A SO_2-damaged pine stand at Domsjö with test plots.

nitrate (Ljungasalpeter) dosed at 150 kg N per hectare. Test plot II was dressed with NPK (10 – 10 – 15), the dose of N being the same as for test plot I. Test plot III represented an unfertilized control plot. In the case of the damper test plots, IV was fertilized with the same amount of NPK as plot II, while plot V served as an unfertilized control plot. The fertilizing was done in mid-June 1967.

5.2. Measuring and analysing

Needle samples and branches were collected from the dry test plots, after which the shoot lengths were measured and an estimate made of the number of needles per annual shoot and the average needle weight. Ten pines were selected from each test plot (I – III), and of these 5 were either completely free from smoke damage or negligibly affected by it ("A-trees"), while 5 were seriously affected ("B-trees"). These were analysed individually and the results are shown in tables 6 – 12. Material for measuring and analysis was collected at three different times – in May and November 1967 and in September 1968. The needles were analysed with regard to total sulphur, sulphate sulphur (cf. LIHNELL, 1969) and total nitrogen.

To find as reliable an indication as possible of the effect of SO_2 on trees, many measurements were taken and the values correlated with the general appearance of the trees. As already mentioned, the trees were divided into

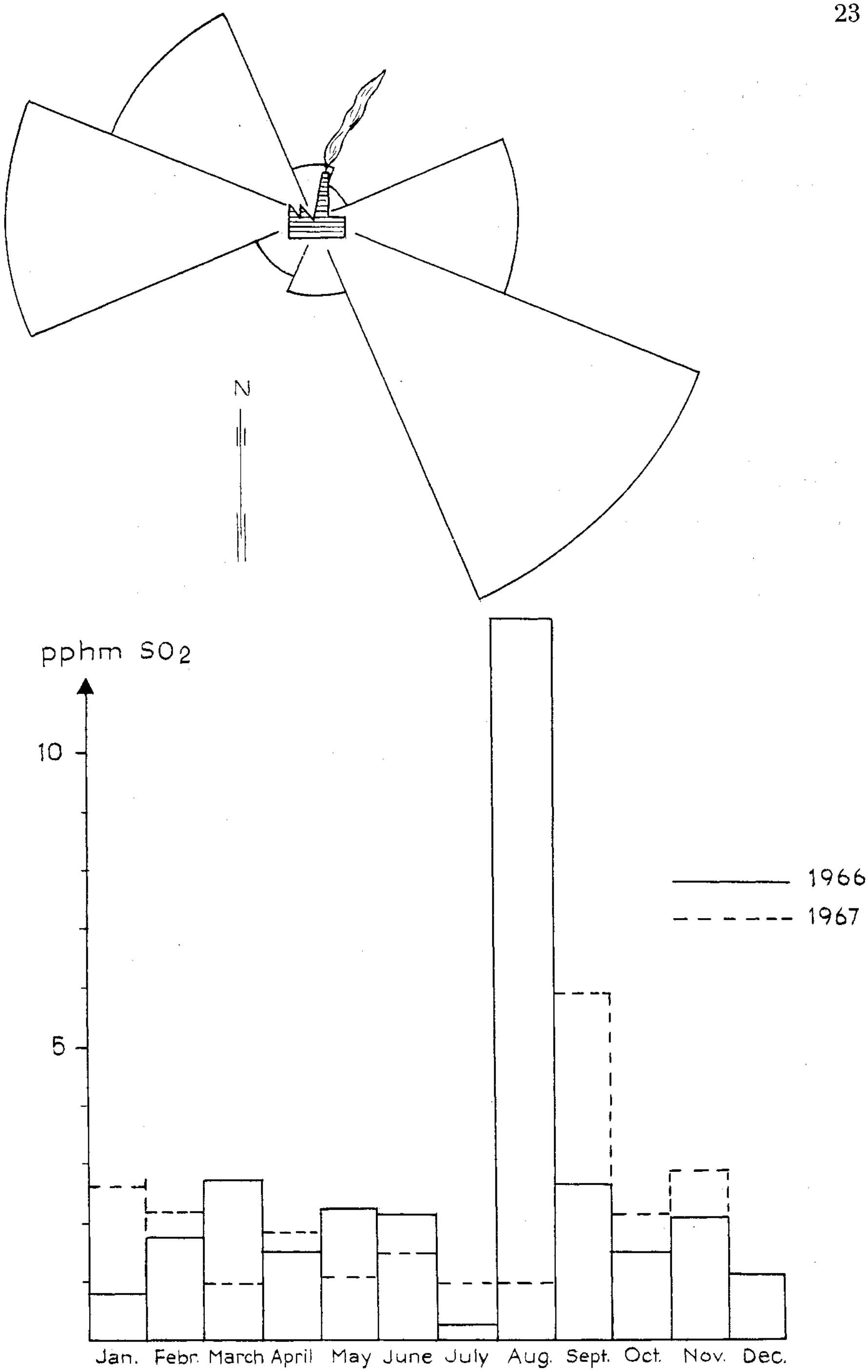

Fig. 4. The prevailing wind direction at Domsjö, Örnsköldsvik, and the monthly mean values of SO_2-content measured at the sawmill, Domsjö.

"A-trees", which when examined ocularly showed little or no evidence of SO_2 damage, and "B-trees", the damage to which could easily be seen. After considering various ways of defining a "compact crown" and generally healthy look about a tree to more or less atrophied development, the following three measurements were carried out:

- the mean shoot length
- the number of needles per annual shoot
- the mean weight of 100 dried needles (at 60 °C for two days) per annual shoot.

In absolute terms these values are of less interest since the length of the annual shoot, and consequently also the number of needles per annual shoot, normally differs from year to year depending on climatic conditions. In this way HESSELMAN (1904) demonstrated that for instance the length of the annual shoot depends on the previous summer's weather. In the tables 6, 8 and 9 a collocation has been made of various absolute data regarding the mean length of annual shoots, the average number of needles per annual shoot and the average needle weight of different annual shoots. The measured absolute values for shoot length and needle weight from the fertilized test plots have in Tables 7 and 10 been put in relation to the values obtained from the corresponding control plots. If the relationship between e.g. the needle weight from a fertilized test plot and a control plot for the same year considerably exceeded 1 after fertilization, but had earlier been under or near 1, this has been regarded as probable proof of the favourable effect of fertilization.

Analyses have also been made of needles from different annual shoots from "A-trees" and "B-trees". The needles were analysed with regard to total sulphur (1967 and 1968), and sulphate sulphur and total nitrogen (1968).

5.3. Results

5.3.1 The mean shoot length

Table 6 shows that as a rule the so-called A-trees, which after ocular examination had been selected as "better" trees, had longer annual shoots than the B-trees. No distinct tendency towards the fertilized trees having longer annual shoots than the unfertilized one or two summers after fertilization could be discerned however (Table 6 and 7).

5.3.2 Number of needles per annual shoot

From Table 8 it can be seen that in general the B-trees had considerably less needles per annual shoot than the A-trees. When recording the number

Table 6. Mean length in mm of annual shoots from undamaged (A) and SO_2 damaged (B) pines on fertilized test plots and two unfertilized comparison plots in Domsjö. Fertilization carried out in May 1967. Measurements taken in May 1967 (annual shoots 1964—1966), November 1967 (annual shoot 1967) and in November 1968 (annual shoot 1968). Values represent mean figure for minimum of 5 trees of same type.

Test plot	Type of tree	Mean length of annual shoot in mm				
		1964	1965	1966	1967	1968
I						
Fertilized with N	A	16.5	16.6	24.3	22.9	29.6
	B	14.4	16.2	20.8	15.9	24.6
II						
Fertilized with NPK	A	20.1	17.9	23.4	24.2	25.4
	B	19.1	19.0	24.6	21.1	25.0
III						
Unfertilized	A	17.6	15.3	21.6	20.4	26.5
	B	15.2	15.9	21.4	15.6	22.1
IV						
Fertilized with NPK	A	19.2	17.5	19.5	22.4	24.3
	B	20.0	18.4	22.0	20.1	24.1
V						
Unfertilized	A	18.6	16.0	20.6	20.2	23.5
	B	20.4	16.1	20.2	19.6	22.7

Table 7. Relationship between mean length of annual shoots of undamaged and SO_2 damaged pine on fertilized test plots (I = N fertilized, II and IV = NPK fertilized) and two unfertilized comparison plots (III and V) in Domsjö. Fertilization carried out in May 1967. cf. Table 6.

Relationship Fertilized/ Unfertilized	Type of tree	Relationship between fertilized and unfertilized pines regarding mean length of annual shoot				
		1964	1965	1966	1967	1968
I/III	A	0.94	1.09	1.13	1.14	1.12
	B	0.94	1.02	0.97	1.02	1.11
II/III	A	1.13	1.17	1.09	1.18	1.12
	B	1.25	1.20	1.14	1.35	1.14
IV/V	A	1.03	1.09	0.94	1.11	1.03
	B	0.98	1.08	1.09	1.03	1.07

of needles in May 1967, when the one-year needles (1966), two-year needles (1965) and three-year needles (1964) were counted, it could be established that the number of needles dropped appreciably with the age of the "annual shoot", and that the B-trees shed their needles more quickly than the A-trees. All the needles of the 4-year shoot had been shed by all trees.

No major difference as regards the number of needles on post-fertilization shoots were readily discernable (Table 8).

Table 8. Average number of needles per annual shoot on undamaged (A) and SO_2 damaged (B) pines on fertilized test plots and two unfertilized comparison plots in Domsjö. Fertilization performed May 1967. Measurements taken in May 1967 (annual shoots 1964—1966), November 1967 (annual shoot 1967) and November 1968 (annual shoot 1968). Values represent mean figure for samples from minimum of 5 trees of same type.

Test plot	Type of tree	Average number of needles per annual shoot				
		1964	1965	1966	1967	1968
I						
Fertilized with N	A	24	52	72	80	78
	B	12	42	68	58	74
II						
Fertilized with NPK	A	28	52	66	72	66
	B	16	—	66	64	58
III						
Unfertilized	A	10	44	74	80	74
	B	4	36	66	72	76
IV						
Fertilized with NPK	A	—	—	70	76	74
	B	—	—	62	70	68
V						
Unfertilized	A	—	—	70	74	70
	B	—	—	64	72	70

5.3.3 Needle weight

The weighing of 100 dried needles from different annual shoots revealed that the weights could vary from year to year depending on the external growth conditions. If comparisons were made between A-trees and B-trees for one and the same year it could be seen that great irregularities occurred, even though there was a tendency for the needles of the B-trees to be lighter in weight (Table 9). Following fertilization, however, the tendency became more obvious, particularly in the case of the N-fertilized trees on test plot I, where the relationship between the needle weight of the A-trees and the needle weight of the corresponding trees on the unfertilized plot even after one summer equalled 1.23, whereas the value for the previous year was 0.79. The corresponding values for the B-trees were 1.46 and 1.16. The needle weight of the trees treated with NPK also increased in relation to the corresponding weights for the unfertilized trees, although not so distinctly until after two summers (Table 10).

5.3.4 Sulphur content

From the analysis values for total S and SO_4-S which have been collocated in Table 11 it can be seen that the sulphur content was generally higher in the older needles. There was, however, no really uniform difference in S-

Table 9. Mean weight of 100 needles from different annual shoots of undamaged (A) and SO_2 damaged (B) pines on fertilized test plots and two unfertilized comparison plots in Domsjö. Fertilization performed in May 1967. Material collected in May 1967 (annual shoots 1965—1966), November 1967 (annual shoot 1967) and November 1968 (annual shoot 1968). Values represent mean figure for samples from minimum of 5 trees of same type.

Test plot	Type of tree	Average weight of 100 dried needles in mg of annual shoots			
		1965	1966	1967	1968
I					
Fertilized with N	A	989	1011	1162	832
	B	1001	1080	1258	666
II					
Fertilized with NPK	A	866	1168	1068	820
	B	1068	871	950	800
III					
Unfertilized	A	1006	1315	944	686
	B	966	934	862	530
IV					
Fertilized with NPK	A	—	—	990	848
	B	—	—	1050	762
V					
Unfertilized	A	—	—	970	692
	B	—	—	890	684

Table 10. Relationship between mean weight of 100 dried needles of different annual shoots from undamaged (A) and SO_2 damaged (B) pines on fertilized test plots (I = N fertilized, II and IV = NPK fertilized) and two unfertilized comparison plots (III and V) in Domsjö. Fertilization performed in May 1967. cf. Table 9.

Relationship Fertilized/ Unfertilized	Type of tree	Relationship between fertilized and unfertilized pines regarding average weight of 100 needles from annual shoots			
		1965	1966	1967	1968
I/III	A	0.98	0.79	1.23	1.21
	B	1.04	1.16	1.46	1.26
II/III	A	0.86	0.89	1.13	1.20
	B	1.11	0.93	1.10	1.51
IV/V	A	—	—	1.00	1.23
	B	—	—	1.18	1.11

content between needles from the apparently healthy trees and those of the trees which had clearly sustained gas damage. Fig. 5 contains a diagram from the examination work performed by ELFVING and SOHLBERG showing the relationship between the sulphur content of the needles and their mean weight (i.e. of 100 g of dried needles) in regard to "better" (A) and "poorer" (B) trees on test plots I, II and III. The diagram shows a clear tendency towards a relationship. A corresponding collocation of the sulphur content and data derived from other measurements did not reveal a corresponding relationship.

Table 11. Total sulphur and sulphate sulphur content in pine needles of different ages from undamaged (A) and SO_2 damaged (B) pines on fertilized and unfertilized test plots in Domsjö. Analyses made of material collected in May 1967 (annual shoots 1964—1966), November 1967 (annual shoots 1967) and in November 1968 (annual shoots 1968). Values represent average figure for 5 test trees of same type.

Test plot	Type of tree	Percentage of needles' dry weight from annual shoots													
		Total S								SO_4–S			Total N		
		Analysis May 1967			Analysis Nov. 1967		Analysis Nov. 1968			Analysis Nov. 1968			Analysis Nov. 1968		
		1964	1965	1966	1966	1967	1966	1967	1968	1966	1967	1968	1966	1967	1968
I Fertilized with N May 1967	A	—	0.13	0.13	0.13	0.09	0.15	0.17	0.15	0.11	0.09	0.08	1.28	1.52	1.61
	B	—	0.15	0.13	0.14	0.10	0.16	0.16	0.13	0.08	0.07	0.07	1.46	1.67	1.89
II Fertilized with NPK May 1967	A	—	0.13	0.13	0.19	0.15	0.16	0.16	0.18	0.11	0.11	0.08	1.36	1.42	1.73
	B	—	—	0.18	0.17	0.11	0.18	0.18	0.15	0.10	0.11	0.08	1.10	1.33	1.53
III Unfertilized	A	0.16	0.15	0.11	0.17	0.14	0.18	0.18	0.14	0.08	0.05	0.05	1.32	1.54	1.95
	B	—	0.13	0.13	—	0.16	0.17	0.17	0.13	0.08	0.06	0.08	1.27	1.66	1.77
IV Fertilized with NPK May 1967	A	0.13	0.13	0.12	0.15	0.11	0.17	0.15	0.13	0.08	0.08	0.06	1.38	1.66	1.75
	B	0.11	0.10	0.11	0.11	0.08	0.16	0.18	0.16	0.07	0.07	0.06	1.32	1.66	1.79
V Unfertilized	A	—	—	—	0.08	0.09	0.16	0.15	0.15	0.12	0.13	0.07	1.09	1.16	1.30
	B	—	—	—	0.15	0.09	0.17	0.16	0.15	0.08	0.12	0.08	1.12	1.08	1.52

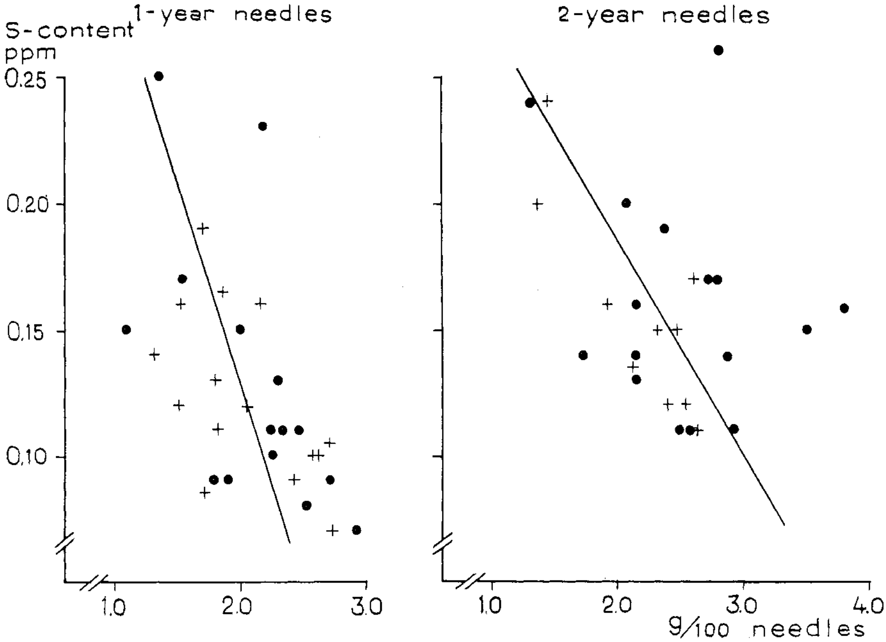

Fig. 5. Diagram showing the relationship between analysed S-content of pine needles and the weight of 100 dried needles from the annual shoot and the second annual shoot
● Well developed trees not affected by SO_2 (A-trees)
+ Trees affected by SO_2 (B-trees).

5.3.5 The development of growth rings

For the purpose of studying the development of growth rings for a 30-year period, a series of increment cores was taken from 10 A-trees and 10 B-trees on test plots I, II, III and IV in November 1968. Test plot V proved to be altogether too heterogeneous to provide comparable samples and was therefore excluded. The growth ring indices were calculated for the respective groups, using the width of the 1929 ring as a basis, and were collocated in a diagram (Fig. 6). The index curves reveal that a distinct change in the growth ring increment, especially for the B-trees, occurred from the first half of the 1950's, and which can hardly be explained by neglected thinnings or a sudden change in the climate. On the other hand, it appears that the change could very well be connected with the circumstance that the Domsjö factory started burning sulphite lye in December 1950. The ensuing strong increase in the SO_2 content of the air seems to be the most plausible reason for the increasingly pronounced decline in the development of the growth rings, a circumstance which even affected the apparently healthy trees.

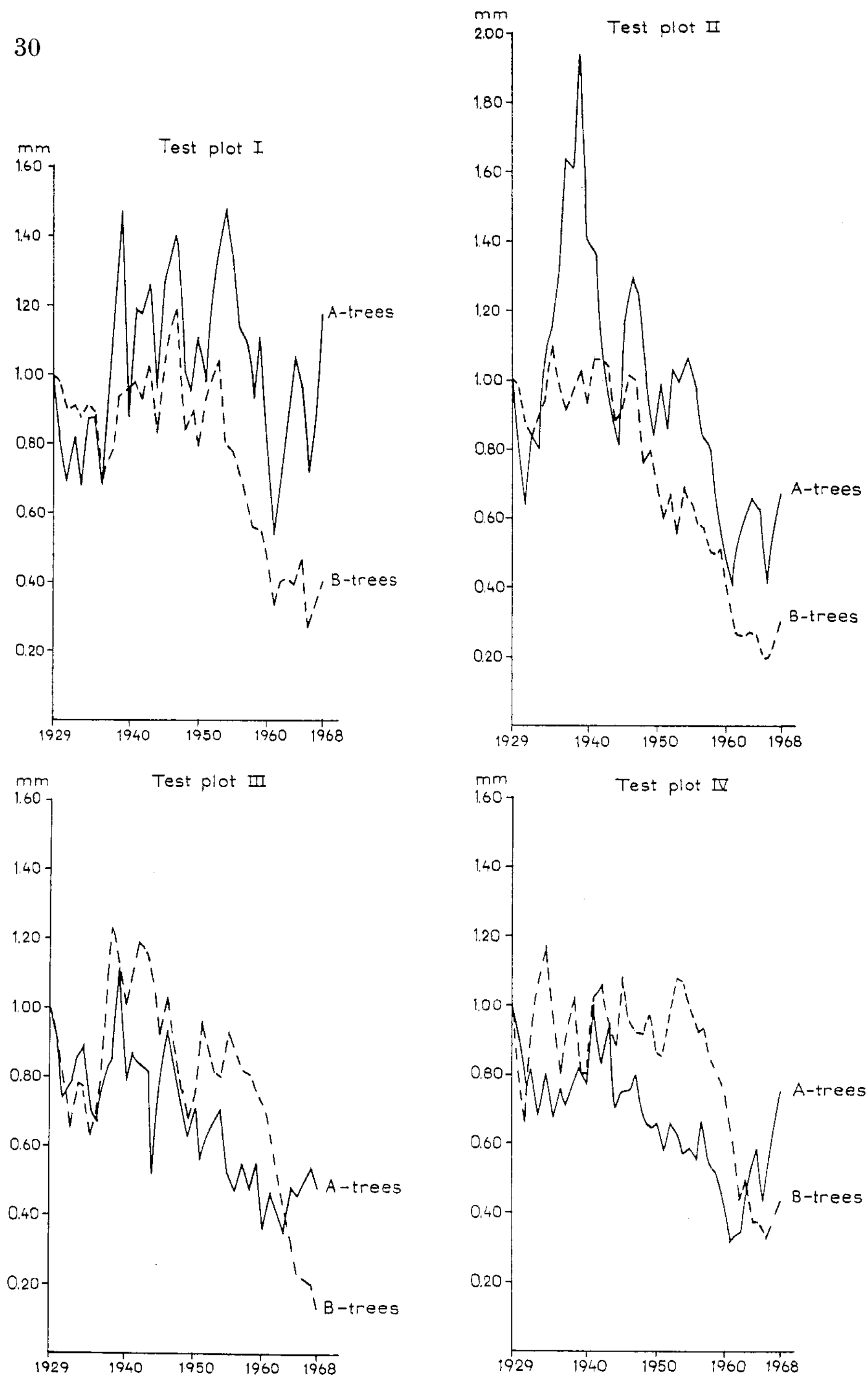

Fig. 6. Diagram showing width of annual rings of undamaged trees (A-trees) and trees affected by SO_2 (B-trees) for a 40-year period on fertilized and unfertilized (III) plots at Domsjö. Fertilization carried out in May 1967.

It can be seen from the diagrams in Fig. 6 that the curve for all fertilized plots (I, II and IV) started to rise while the width of the growth rings of trees on the corresponding unfertilized plot (III) was still declining. Fertilization could therefore apparently lead to a certain increase in the growth rate even in the case of trees which had sustained severe SO_2 damage.

6. Fertilization experiments on SO_2 damaged pine in the town of Lidingö

Seventeen test plots were arranged in Baggebyberg and the Torsviks-svängen area of Lidingö for the purpose of making a continuous record of the total sulphur content and also, from and including 1969, the sulphate sulphur content of needles from fertilized and unfertilized pine. As can be seen from Fig. 7 both areas are strongly exposed to Stockholm. Moreover, the first area is situated opposite industrial establishments on the other side of the open water, while the second one faces the Värta gasworks at a distance of roughly 1 km.

The following values from samples taken by Elfving and Sohlberg in the summer of 1967 and analysed by the State Agricultural Chemical Laboratory serve as a comparison with the S content of pine in the test areas mentioned above.

	Total sulphur in pine needless, % of dry weight
Johanneshov, south of Stockholm, depression	0.18
,, ,, ,, ,, , hill	0.15
Skansen, Stockholm	0.14
Värta gasworks, Stockholm	0.15
Torsvikssvängen, Lidingö, (test area)	0.15
Baggeby, ,, , shore	0.15
,, ,, , hill (test area)	0.13
Brevik, ,, , green area	0.08
Uddevalla, 4 km north of the town	0.12
Erken, 70 km northeast of Uppsala	0.09
Västra Fiskåvattnet, north Jämtland, 450 m above sea level	0.07

6.1. Description of the test plots

The test plots were laid out in thinly stocked stands consisting mainly of older pine trees. Only trees which had not been attacked by fungi and insects were selected for analysis.

6.1.1 Torsvikssvängen, older pines

The stand comprised a high green area in the centre of a number of multi-storey dwelling houses. The pine trees were growing in crevices together with tall birch and oak shrub. The dominating lower vegetation consisted of

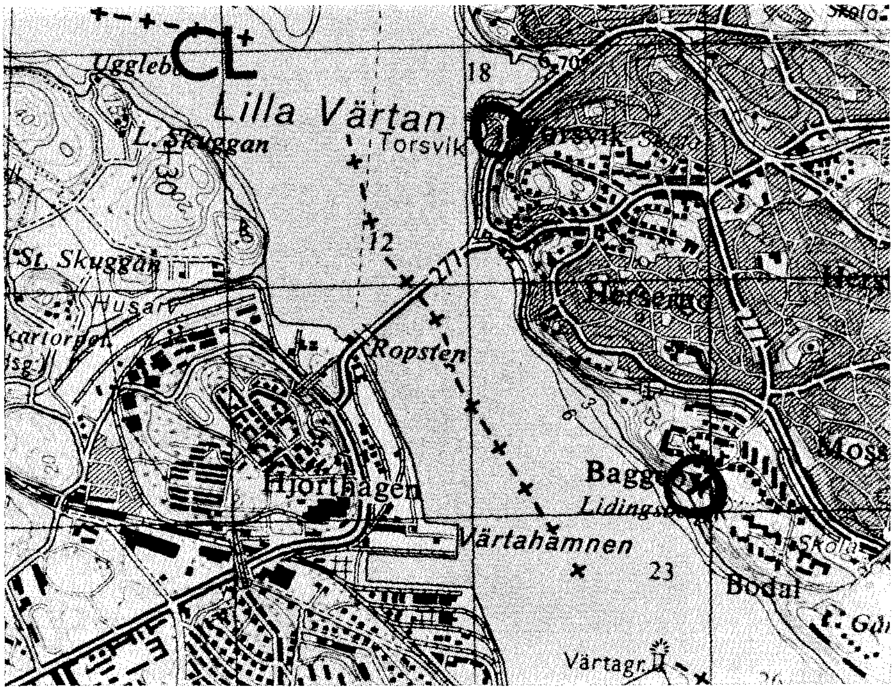

Fig. 7. Map of the test area at Stora Värtan, Lidingö.

Calluna vulgaris, *Vaccinium vitis ideaa*, grass and various kinds of moss. *Rumex acetocella* grew in abundance after fertilization. The average age of the trees was 120 years and the mean height about 9 m.

6.1.2 *Torsvikssvängen, younger pines*

The site was somewhat flatter than the previous one and the humus layer slightly thicker. The trees were 0.3 – 3 m in height and represented the undergrowth in an older mixed stand of pine and birch. The vegetation was for the most part the same as for the previous test plot.

6.1.3 *Baggeby, older pines*

The test plot was situated just above the cliff down to Värtan and had a strong westerly exposure. The pines used in the test grew in much the same way as already described, i.e. chiefly in crevices. There was an abundance of oak shrub. The sub-vegetation consisted chiefly of sparse occurrences of *Calluna vulgaris*, *Vaccinium vitis idaea* and grass. The trees were between

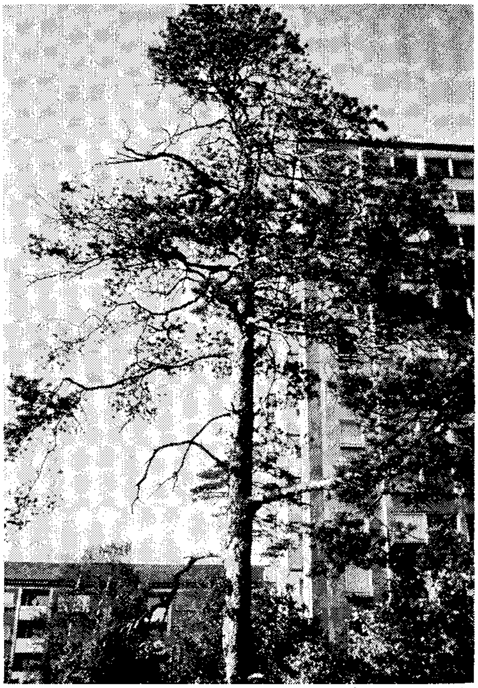

Fig. 8. SO_2-damaged pine near multi-storey house in the Baggeby test area, Lidingö.

120 and 125 years old and had a mean height of approximately 7 m (Fig. 8).

6.1.4 Fertilization

On account of the topographical conditions—rocky ground with interlying crevices—it was impossible to arrange normal fertilization test plots in this particular instance, for which reason it was necessary to fertilize individual trees. All the fertilized plots were dressed with Weibull's NPK (12—12—19) as follows. Pine trees of the same type were grouped together in pairs, of which one pine was fertilized and the other left untouched as a control tree. In cases where several trees grew in the same crevice they were given identical treatment. If a tree in a crevice had a minor root in a nearby crevice where a comparison tree was growing the root was severed. In the event of it being necessary to choose between trees, those in lower crevices were fertilized, while those in higher crevices were used as control trees. The fertilizing was carried out 26 May 1967 by Elfving and Sohlberg, at which time the larger pines were dressed with fertilizer in a circle having a radius of 3 m. The younger pines were given fertilizer within a circle with a

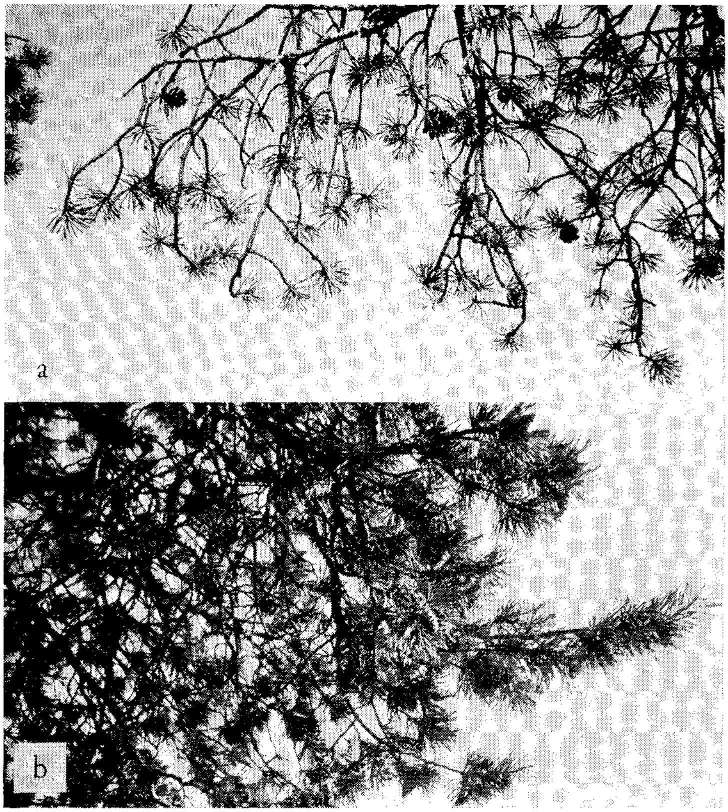

Fig. 9. Needle density of SO_2-damaged (a) and healthy pines (b) at Torsvikssvängen, Lidingö.

radius of 2 m. In both cases the dose was calculated on the basis of 150 kg N per hectare.

6.2. Measuring and analysing

When samples were taken for analysis, care was taken to ensure that approximately the same number of samples were taken from the "better" (A) trees as from the "poorer" (B) trees, which had been distinguished with regard to the stand's "degree of stocking" and general appearance. In 1967 samples were taken from a total of 20 older and 10 younger pines at Torsvikssvängen and 12 pines at Baggeby. In April 1969, 38 samples were taken for analysis. The needle samples were collected by hand from the upper half of the crown, 10–15 branches being taken from each test tree. The samples were of such a size that they included all the annual shoots complete with the remaining needles. For the sulphur analyses carried out in 1967,

Table 12. Average length of annual shoot in mm from undamaged (A) and SO_2 damaged (B) fertilized and unfertilized pines in Lidingö town district and relationship between the average length from fertilized and unfertilized trees. Measurements taken in April 1969 Values represent average figure for samples from all trees on the various test plots. Fertilization with NPK (12—12—19) performed in May 1967.

Test plot	Type of tree		Average length of annual shoot in mm			Type of tree	Average length of annual shoot fertilized/unfertilized trees		
			1966	1967	1968		1966	1967	1968
Torsvikssvängen									
older trees	fertilized	A	27	20	20				
		B	17	22	18	A	1.23	1.25	1.43
	unfertilized	A	22	16	14	B	1.00	1.29	1.39
		B	17	17	13				
younger trees	fertilized	A+B	56	75	89				
	unfertilized	A+B	51	51	49	A+B	1.10	1.47	1.82
Baggeby	fertilized	A	26	23	20				
		B	19	18	16	A	1.04	1.00	1.10
	unfertilized	A	25	23	18	B	1.06	1.28	1.23
		B	18	14	13				

Table 13. Number of needles per annual shoot on average of undamaged (A) and SO_2 damaged (B) fertilized and unfertilized pines in Lidingö town district and the relationship between the number of needles on fertilized and unfertilized trees. Measurements made in April 1969. Values represent average figure for samples from all trees on the various test plots. Fertilization with NPK (12—12—19) performed in May 1969.

Test plot	Type of tree		Average number of needles per annual shoot			Type of tree	Average number of needles per annual shoot fertilized/unfertilized trees		
			1966	1967	1968		1966	1967	1968
Torsvikssvängen									
older trees	fertilized	A	54	54	60				
		B	52	44	48	A	1.08	1.23	1.25
	unfertilized	A	50	44	48	B	1.08	1.10	1.41
		B	48	40	34				
younger trees	fertilized	A+B	42	100	116				
	unfertilized	A+B	42	80	96	A+B	1.00	1.25	1.21
Baggeby	fertilized	A	38	20	56				
		B	24	28	56	A	0.86	0.84	1.00
	unfertilized	A	44	24	56	B	—	1.08	1.17
		B	—	26	48				

use was made of 10–15 needles from each needle season of each sample branch, which meant that 5–10 g of needles were analysed. Larger samples of the same type were used for the 1969 analyses.

Table 14. Average weight of 100 needles from different annual shoots of undamaged (A) and SO_2 damaged (B) fertilized and unfertilized pines within Lidingö town and the relationship between needle weight from fertilized and unfertilized trees. Material collected in April 1969. Values represent average figure for samples from all trees on the various test plots. Fertilization with NPK (12—12—19) performed in May 1967.

Test plot	Type of tree		Average weight of 100 needles from annual shoots, mg			Type of tree	Average weight of 100 needles from annual shoots fertilized/unfertilized trees		
			1966	1967	1968		1966	1967	1968
Torsvikssvängen									
older trees	fertilized	A	752	697	771				
		B	823	873	969	A	0.86	0.98	1.15
	unfertilized	A	878	710	668	B	0.98	1.26	1.30
		B	838	691	746				
younger trees	fertilized	A + B	704	713	924				
	unfertilized	A + B	791	808	898	A + B	0.89	0.88	1.03
Baggeby	fertilized	A	791	715	936				
		B	808	803	672	A	1.04	1.33	1.60
	unfertilized	A	759	538	582	B	—	1.18	1.27
		B	—	682	528				

As for the Domsjö material, the branch samples were recorded with regard to the mean length of the different annual shoots, the number of needles per annual shoot, the weight of 100 dried needles from the respective annual shoots, and the content of total sulphur and sulphate sulphur before and after fertilization was determined. Moreover, the total nitrogen content of the needles one year after fertilization was determined.

Tables 12—15 contain a collection of the various measurements and analyses.

6.3. Results

6.3.1 Mean shoot length

As can be seen from Table 12, the "better" trees (A) had consistently longer shoots than the apparently "poorer" trees (B). A distinct tendency towards a greater shoot length after fertilization could also be established, at least in the case of the Torsvikssvängen area.

6.3.2 Number of needles per annual shoot

Table 13 shows that the B-trees, which consistently shed their needles more quickly than the A-trees, in general had a smaller number of needles

Table 15. Total sulphur and sulphate sulphur content and total nitrogen content of pine needles of various ages from undamaged (A) and SO_2 damaged (B) fertilized and unfertilized pines within Lidingö town. Analyses made of material collected in May 1967 (annual shoots 1964—1966), November 1967 (annual shoots 1965—1967) and April 1969 (annual shoots 1968). Values represent average figure for samples from all trees on the various test plots. Fertilization with NPK (12—12—19) performed in May 1967.

Test plot	Type of tree		Percentage of needles' dry weight from annual shoots														
			Total sulphur									Sulphate sulphur			Total nitrogen		
			Analysis May 1967			Analysis Nov. 1967			Analysis Apr. 1969			Analysis Apr. 1969			Analysis Apr. 1969		
			1964	1965	1966	1965	1966	1967	1966	1967	1968	1966	1967	1968	1966	1967	1968
Torsvikssvängen older trees	fertilized	A	0.20	0.13	0.14	0.21	0.22	0.20	0.15	0.14	0.14	0.08	0.07	0.06	—	1.47	1.51
		B	—	0.15	0.14	—	0.19	0.19	0.15	0.16	0.14	0.09	0.09	0.07	1.63	1.68	1.78
	unfertilized	A	0.20	0.13	0.14	0.21	0.20	0.19	0.15	0.15	0.14	0.09	0.07	0.08	1.46	1.54	1.63
		B	—	0.15	0.14	—	0.19	0.19	0.16	0.15	0.15	0.10	0.09	0.09	2.04	1.83	1.63
younger trees	fertilized	A + B	0.19	0.16	0.15	0.20	0.23	0.19	0.19	0.18	0.17	—	0.10	0.09	—	1.70	1.72
	unfertilized	A + B	0.19	0.16	0.15	0.23	0.23	0.19	0.21	0.19	0.17	—	0.10	0.09	—	1.61	1.65
Baggeby	fertilized	A	0.12	0.12	0.11	0.21	0.21	0.22	0.17	0.16	0.14	0.10	0.10	0.10	1.59	1.72	1.86
		B	—	0.13	0.15	0.18	0.19	0.17	0.17	0.15	0.14	0.10	0.08	0.08	1.78	1.76	1.86
	unfertilized	A	0.12	0.12	0.11	0.18	0.19	0.21	0.16	0.16	0.15	—	0.10	0.09	—	1.74	1.71
		B	—	0.13	0.15	—	0.19	0.19	0.15	0.16	0.14	0.10	0.09	0.08	—	1.76	1.80

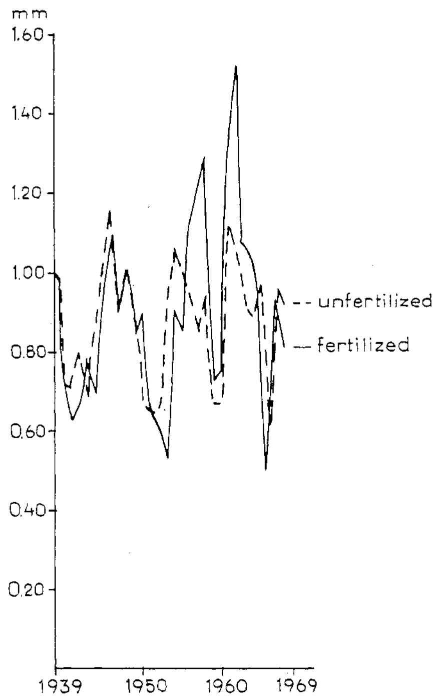

Fig. 10. Diagram showing width of annual rings of fertilized and unfertilized pines for a 30-year period on fertilized and unfertilized test plots at Lidingö. Fertilization carried out in May 1967.

per shoot than the A-trees (Fig. 9 a – b), and that a clear disposition towards denser needle formation occurred after fertilization.

6.3.3 *Needle weight*

It can be seen from Table 14 that the B-trees did not always have a lower needle weight than the A-trees. On the other hand, there was a distinct tendency for both older and younger trees to attain a higher needle weight following fertilization.

6.3.4 *Sulphur content*

Table 15 shows that fertilization had only a negligible effect on the total sulphur and sulphate sulphur content. Neither was there any marked difference between A-trees and B-trees. As in the case of the Domsjö material, a tendency towards a higher sulphur content in the older trees was discernible. The opposite was noted as regards the nitrogen content of the needles.

6.3.5 The development of growth rings

The growth ring measurements for all test trees have been collocated in Fig. 10 in such a way that the values for all fertilized and unfertilized older trees in Torsvikssvängen and the Baggeby area have been brought together, although the A and B trees have been kept separate. 1939 has been used as the base year (= 1.00 in Fig. 10) for the older trees and 1959 in the case of the Torsvikssvängen trees. Because of the limited nature of the material, and the very considerable differences in site conditions for individual trees, however, these values must be regarded as being fairly unreliable.

7. Discussion and summing-up

The effect of smoke and flue gases on vegetation has become an increasingly acute problem in the present-day society. Particular interest attaches to the question of gas damage to forest trees, partly in industrial areas, partly and not least in built-up areas, where trees frequently constitute an important environmental feature. Great attention has been paid to signs of smoke damage, e.g. the absence of certain species of lichens which normally occur in similar areas where the effects of flue gases are not present, as also the external factors which influence the occurrence of damage. However, only a few experiments have dealt with the prospects of preventing or combating gas damage to forest trees by direct measures.

This paper has on the basis of studies made of the ecological factors which affect smoke damage to conifers, attempted to reduce the extent of the damage by improving the condition of the trees, and thereby eventually to give them a higher degree of resistance to injurious external influence. Since one of the most obvious ways of bringing this about can be assumed to be the application of growth nutrients in areas which are under-nourished, some fertilization experiments were made on trees, predominantly pine, which had been damaged to a greater or lesser extent by SO_2. A preliminary analysis of the importance of various ecological influences compared with the part played by hereditary factors was also made.

The laboratory tests revealed that both pine (*Pinus silvestris*) and spruce (*Picea abies*) are to a great extent affected by SO_2, which in Sweden is of prime importance as regards damage to forests in both industrial and built-up areas where the burning of fuel oil often gives rise to not inconsiderable amounts of SO_2 in the atmosphere. Spruce appears to be somewhat more sensitive than pine. Damage can be influenced to a great extent by the effects of airborne particles; ash which had been saturated with SO_2 at different temperatures was used in the experiments. Particularly favourable conditions for the occurrence of severe damage result in cases where the ash is saturated with SO_2 in the relatively low temperature obtaining at the top of tall chimneys. The effect of different nutrients could not be determined with the help of laboratory experiments. Completely acceptable technical devices for assessing the influence of nutrient supply in relation to other factors present in an artificial environment are extremely difficult to obtain.

The outcome of field tests made partly in an industrial district 1 km from the Mo and Domsjö chemical plant in Alfredshem, and partly in a residential area within the Lidingö town boundaries, indicated that in certain respects it is possible to influence the trees' sensitivity to SO_2 damage. Thus it was possible to trace a certain connection between fertilization and needle weight;

Fig. 11. Completely healthy pine among severely SO_2-damaged pines on a test plot at Domsjö.

this can be regarded as a relatively good indication of the "compactness" or "sparseness" of the tree crowns which is often resorted to when assessing smoke damaged trees.

Concerning the Lidingö trees it was also possible to discern a certain tendency towards longer annual shoots and a higher number of needles in the case of fertilized trees.

The diameter growth was favourably affected by fertilization in the case of the Domsjö pines, which grew in a mixed stand. As regards the Lidingö pines, which were individually fertilized and growing on vastly differing sites, it was not possible to trace changes in the development of the growth rings two years after fertilization.

No effect on the sulphur content of the needles could be directly attributed to fertilization. A distinct tendency towards a higher sulphur content, both as regards total sulphur as well as sulphate sulphur, could be seen in older needles in keeping with earlier observations. Lower values with regard to the total nitrogen content could, however, be established in the older needles of both fertilized and unfertilized trees.

It would consequently seem to be possible to influence the general "condition" of the trees to some extent by fertilizing the poorly nourished stand sites, thereby indirectly effecting a certain increase in resistance to SO_2 damage. This effect is extremely difficult to calculate, however, and would be valid only under certain conditions, e.g. that the soil is under-nourished and that if fertilizers are used they are applied in the correct amounts, that the trees are not to severely damaged by SO_2 etc. The present series of experiments has shown, however, that the use of fertilizers in the right proportions can help to counteract SO_2 damage, at least to pine trees.

There is no doubt that in the long term the safest protection against gas damage would be afforded by the systematic selection of seeds or grafts from particularly resistant trees. The usual damage pattern in a stand which has sustained gas damage is that completely undamaged trees often thrive near to, or sometimes in the centre of, severely damaged or dead trees (Fig. 11). It is most probable that such undamaged trees have a distinctly greater resistance of an hereditary nature to SO_2 or other gases. For this reason these problems have been incorporated in the resistance research currently being conducted at the Department of Forest Botany of the Royal College of Forestry in Stockholm. Grafts have therefore been obtained from such undamaged trees for use in controlled SO_2 resistance tests in laboratory and field conditions.

ACKNOWLEGMENTS

Help in conducting the work was given by Ytongbolagen, whose former leader, the late AUGUST CARLÉN, and present head, BERTIL CARLÉN, together with the head of the laboratory, GORDON ANDERSON, supported the work in every possible way, e.g. by conducting the chemical analyses. Valuable support at these investigations was also given by Dr. ERIC RONGE and engineer LISELOTTE BEYER. Analyses have also been made at the Mo and Domsjö research laboratories by Dr. INGVAR JULLANDER and civil engineer GÖRAN HULT. In the field work conducted in the Domsjö area assistance was given by the forest officer OLLE NILSSON and the forest ranger ULF VON POST. The Lidingö Town authorities supported the work in that area. The initiative for the study there was taken by the forest officer JOHAN EDÉN and Director BENGT GEIJER. Valuable assistance was provided by chief municipal gardener ROLF MELLQVIST and the forest officers BJÖRN ELFVING and SUNE SOHLBERG, who have carried out a great deal of the field work and measurings as to the Domsjö and Lidingö experiments. Finally, a contribution permitting the completion of the work was received from the Swedish Natural Science Research Council. I should like to express my sincere gratitude for the support given to the investigation and the interest shown in it.

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Sammanfattning

Effekten av gödsling på svaveldioxidskadade barrträd i industri- och bostadsområden

Inverkan av svaveldioxid på tall, gran och al har studerats dels genom laboratorieexperiment dels genom iakttagelser och försök i fält. En översikt ges över de yttre faktorer som kan påverka gasskador, gaskoncentration, begasningstider, temperatur, vindförhållanden, damm- och sotpartiklar, ljus, luftfuktighet samt näringstillgång i marken.

I laboratorieförsöken konstaterades, att plantorna påverkades snabbare vid högre gaskoncentration än vid lägre och att plantor täckta med aska, som kan absorbera gasen, var mycket känsligare än plantor utan aska. Det framgick vidare, att aktivt kol mättat med SO_2 vid 20°C i kontakt med levande granbarr hade en starkt skadlig effekt på dessa. Om mättningen med SO_2 hade skett vid 100° eller 200°C, blev skadan ej så stor. Aska från öppna brännugnar vid marknivå, där temperaturen är hög, bör därför vara mindre riskabel än aska från höga skorstenar där temperaturen vanligen är lägre.

I fältförsök undersöktes inverkan av gödsling på barrträds känslighet för SO_2 dels i Kvarntorp-området, dels i Örnsköldsvikstrakten och dels inom Lidingö stad. Det framgick av dessa undersökningar att gödsling i skogsbestånd på rik mark icke hade något inflytande på känsligheten för SO_2. Däremot medförde gödsling med kväve resp. fullgödsel (NPK) i tall-gran-bestånd å relativt näringsfattig mark c:a 1 km från Mo och Domsjö fabriker i Alfredshem högre barrvikter hos gödslade träd. Årsringsutvecklingen visade de intressantaste värdena. Sålunda framträdde efter gödsling en tydlig tendens till ökning av årsringsbredden hos både »bättre» träd (A) och »sämre» (B) träd, som mera påverkats av SO_2 (fig. 6). En sådan tendens kunde dock icke iakttagas hos de enstaka gödslade träden å hällmarker inom Lidingö men däremot en viss ökning av skottlängden, barrtätheten och barrvikten. SO_2-analyser visade, att svavelhalten i barren i allmänhet var högre i de äldre barren, men ingen regelbundenhet förelåg i totalsvavel- eller sulfatsvavelhalten hos gödslade och ogödslade träd eller hos till synes friska träd och hos sådana som tydligt påverkats av SO_2. I Domsjö-försöket visade de mera opåverkade träden en tydlig tendens till lägre svavelhalter i barr med högre medelvikt.

På alla försöksfält kunde ofta iakttagas enstaka träd — i allmänhet tallar — som till synes förblivit helt opåverkade av SO_2 mitt ibland träd som starkt skadats eller dött av gasskador. Då det synes sannolikt att detta fenomen beror på genetiskt betingad resistens, har experiment igångsatts med ympar från sådana oskadade träd som utsättes för begasning av varierad styrka och varaktighet.