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RESPONSES OF TRANSPLANTED LICHENS TO SULPHUR DIOXIDE DOSAGES – A NEW SEMI-STATISTICAL DOSAGE/INJURY MODEL

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A semi-statistical model is suggested for injury to monitor plants for long-time field exposures (months). The model is based on the following assumptions:

1. The concentrations of air pollutants in the atmosphere follow the Johnson S_B distribution.
2. The degree of plant injury is proportional to the logarithm of air pollutant dose.
3. No injuries occur below a certain dose level.
4. A dose is defined as the air pollutant concentration multiplied by the duration of exposure raised to an exponent.

Based on the air pollutant frequency distribution a total dose for the exposure period is calculated by integration, and the total dose is related to the observed plant injury by non-linear regression.

The model is tested for long-time exposures of sulphur dioxide to transplanted lichens in natural environments.

INTRODUCTION

Lichens seem to react specifically to sulphur dioxide pollution (SO_2). The action of the pollutant is performed through dosages in relation to physiological and morphological properties of the thallus. The dose is usually defined as the product of pollutant concentration and exposure time. For higher plants in short-term fumigation situations the two factors – concentration and time of exposure – have been seen not to be of equal importance, and furthermore, a threshold concentration below which no visible injury occurs has been introduced. For lichens, comparison of the lichen vegetation located adjacent to physico/chemical measurement stations of SO_2 has suggested that selected lichen species can be calibrated to a winter SO_2 level in southern Scandinavia (HAWKSWORTH and ROSE, 1970; JOHNSON and SØCHTING, 1973). Futher, the lichen Hypogymnia physodes (L.) has been transplanted with standardized transplantation and exposure techniques into urban areas to evaluate the air quality. (KROG and BRANDT, 1975; SØCHTING and JOHNSON, 1978; RAMKÆR et al., 1980) By assuming a direct proportionality between dose – calculated as winter SO_2 average – and rated extent of damage on thallus, SØCHTING and JOHNSON (1978) could explain about 50 % of the variation in thallus injury by the SO_2 level on different monitor sites. RAMKÆR et al. (1980) found that 81 % of the variation in thallus injury could be explained by SO_2 level by using a logaritmic dose/injury relationship.

Since the effect of pollutants on plants is a function of dosages it is not satisfactory to use seasonal SO_2 averages only. Usually air pollution data are reported in the form of frequency distributions. A method to calculate the relevant dosage from a frequency distribution will be shown, and a non-linear dose/injury relationship with a threshold value of the dose will be suggested.

CALCULATION OF DOSAGE

Let the air pollution concentrations C be arranged in a probability density function PDF with a minimum value C_{min} and a maximum value C_{max}, Fig. 1.

Usually the distribution of air pollution concentrations are assumed to be logarithmic normal, that means $Y = k \cdot \ln C$ follows a normally distributed PDF with the geometric mean m_g and the geometric standard deviation s_g (a twoparameter logonormal distribution). If C does not follow a lognormal distribution, a suitable model to fit the data is the Johnson S_B model as pointed out by Mage (1980a). The Johnson S_B model transforms the variable C to

$$\chi = \ln \left(\frac{C - C_{min}}{C_{max} - C} \right)$$

where X is normally distributed with mean μ and standard deviation σ (a four parameter lognormal model, C_{min} and C_{max} are the third and fourth parameters of the distribution). In the following it is assumed that the PDF is logonormal, which means that the data have been transformed as shown, if necessary.

If the effect of a dosage is independent of other dosages we can discuss the problem of the impact of SO_2 air pollution on transplanted lichens in a receptor point for a given period of time (months) in terms of the moment $E(C^q)$ of the PDF. The q'th moment of the distributions is

$$(1) \qquad E(C^q) = \int_{C_{min}}^{C_{max}} C^q \, PDF(C) dc$$

$$\text{or } \sum_n C^q \, PDF(C)$$

q is a weighting factor between concentration and time because one specific concentration C_i in a time period t_i (hours, days) adds the value

$$(2) \qquad D_i = (C_i)^q \cdot t_i$$

to the dosage, which we define as the $E(C^q)$ times the exposure period.

If the PDF is lognormal then

$$(3) \qquad C = m_g \cdot s_g^z$$

where z is a normally distributed parameter with a mean of zero and a standard deviation of 1. The standard normal PDF is

$$(4) \qquad F(z) = \frac{1}{\sqrt{2\pi}} \exp(-\tfrac{1}{2} z^2)$$

then

$$(5) \qquad PDF(C) = F(z)$$

where z is related to C through wq. (3).

If N is the total number of hours or days with SO_2 measurements in the transplantation period, then rewriting eq. (1) integrating and rearranging:

$$\text{DOSAGE } D = E(C^q) \cdot N$$

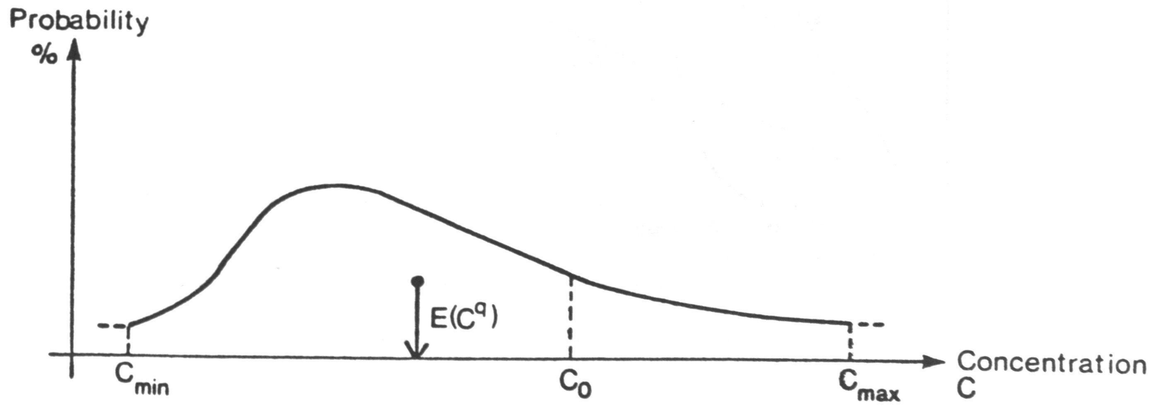

Fig. 1 Probability Density Function of an air pollutant. $E(C^q)$ = moment, C_o = threshold concentration

(6) $$= \int_{z_{min}}^{z_{max}} (m_g \cdot s_g^z)^q \cdot N \cdot \frac{1}{\sqrt{2\pi}} \exp(-{}^1/_2 z^2) dz$$

(7) $$= (m_g \cdot s_g^{\,1/2 q \ln s_g})^q \cdot N \cdot \left[\Phi(\psi_1) - \Phi(\psi_2) \right]$$

where

(8) $$\psi_1 = \frac{1}{\ln s_g} \ln \left[\frac{C_{max}}{m_g \cdot s_g^{q \ln s_g}} \right]$$

(9) $$\psi_2 = \frac{1}{\ln s_g} \ln \left[\frac{C_{min}}{m_g \cdot s_g^{q \ln s_g}} \right]$$

(10) $$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp(-{}^1/_2 x^2) dx$$

If q = 1, that means concentration and time are of equal importance, eq. (7) becomes

(11) $$D = m_g \cdot s_g^{\,1/2 \ln s_g} \cdot N \cdot \left[\Phi(\psi_1') - \Phi(\psi_2') \right]$$

(12) $$= \bar{X} \cdot N \cdot \left[\Phi(\psi_1') - \Phi(\psi_2') \right]$$

(13) = arithmetic mean times exposure time times a correction factor in relation to the limited PDF

The effects then are most likely related as a first-hand approximation of the dosage to the arithmetic average concentration as suggested by MAGE (1980 b). In fact, the first moment in a PDF is by definition the arithmetic mean.

DOSE/EFFECT RELATIONSHIP

A dose/effect relationship is a relation between dose and the degree of injury. For lichens transplanted as biological indicators the injury is the rated extent of dead thallus from zero to 100 per cent. The shape of dose/effect relationship cannot be established without a reasonable number of test points and even then the relationship is based on some ideas about the nature of the relationship. Fig. 2 shows three different relationships.

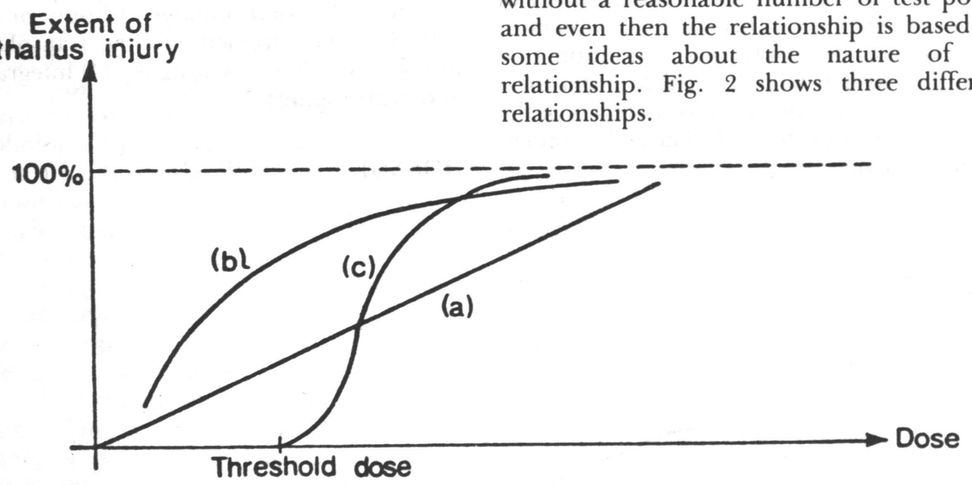

Fig. 2. Dose/effect Relationship
(a) linear relationship i.e. direct proportionality between dose and effect over the entire dose range
(b) logarithmic relationship i.e. direct proportionality between log (dose) and effect over the entire dose range
(c) non-linear relationship with a threshold value of the dose and 100 % injury as asymptotic values

Other relationships could be suggested e.g. the "growth" or logistic curve or the lognormal probability function.

The relationship (c) has been chosen because of three reasonable characteristics:

1. The extent of injury is a function of the logarithm of the dose.
2. The concept of a threshold dose.
3. An upper asymptotic degree of injury.

The equation for (c) is:

(14) $$Y = a \cdot \exp\left(-\frac{b}{\ln(D/D_o)}\right)$$

where
Y = thallus injury in per cent
a = upper asymptote
b = a slope that relates $\ln^{-1}(D/D_o)$ to ln y
D = dose
D_o = threshold dose

TEST OF THE MODEL

The suggested theory of dosage calculation and the relationship to thallus injury was tested by data from two years of transplantation experiments with Hypogymnia physodes in Copenhagen, carried out by RAMK R et al. (1980). The SO_2 air pollution (24 hrs) measurements have been carried out by the Greater Copenhagen Air Pollution Authority and have been supplied by the Danish Meteorological Institute. Table 1 shows the results.

From the values in Table 1 the following parameters in eq. (7) and eq. (4) were found by regression analysis.

The two estimated values of b are significantly different ($t = 9.04^{***}$, $f = 6$). The values of q and D_o cannot be tested against each other. But from the values of D_o the corresponding values of $C_{threshold}$ for the PDF's in Table 1 have been calculated and tabulated in Table 3.

Table 2. Estimated Parameters.

1877/78	q	= 0.16
	D_o	= 295 $(\mu g/m^3)^{0.16}$ x 24 hours
	a	= 102 % $\begin{cases} <109\ \% \\ >96\ \% \end{cases}$, P > 0.95
	b	= 0.015 ± 0.005, P > 0.95
	r^2	= 0.9724
	n	= 5
1978/79	q	= 0.09
	D_o	= 203 $(\mu g/m^3)^{0.09}$ x 24 hours
	a	= 258 % $\begin{cases} <272 \\ >246 \end{cases}$, P > 0.95
	b	= 0.228 ±0.065, P > 0.95
	r^2	= 0.9761
	n	= 5

Table 1. Air Pollution Data and Injury on Transplanted h. physodes. Transplantation perioid: 20 Oct. to 20 Apr.

Winter	STATION	m_g $\mu g/m^3$	s_s $\mu g/m^3$	C_{min} $\mu g/m^3$	C_{max} $\mu g/m^3$	Mean injury %
1977/78	STORM	40.4	1.51	16	158	84.4
	VALB	55.7	1.58	10	222	90.3
	GLOS	35.2	1.68	5	178	88.6
	HELL	48.9	1.68	11	203	96.5
	STAV	22.9	1.97	2	139	53.7
1978/79	STORM	32.8	1.75	2	130	81.2
	VALB	51.4	1.75	8	200	98.5
	GLOS	32.1	1.75	6	148	86.2
	GLAD	45.6	1.79	6	171	98.9
	STAV	21.3	1.92	5	120	60.3

Table 3. Calculated threshold concentration for a given threshold dose

Station	C_o, Estimated threshold concentration ($\mu g/m^3$) 1977/78	1978/79
STORM	69.6	54.6
VALB	90.8	80.4
GLOS	72.3	53.7
HELL	89.4	–
GLAD	–	73.9
STAV	84.9	43.2
Mean	81.1	61.2

It cannot be shown that the two mean values in Table 3 are significantly different (t=2.206, f=8). They are then pooled to give a best estimate of a threshold concentration: $^1/_2(81.4+61.2) = 71.3\ \mu g/m^3$.

Fig 3 shows the two regression lines for the two transplantation experiments. The dotted lines show the theoretical 95 % limits for the variation around each regression line.

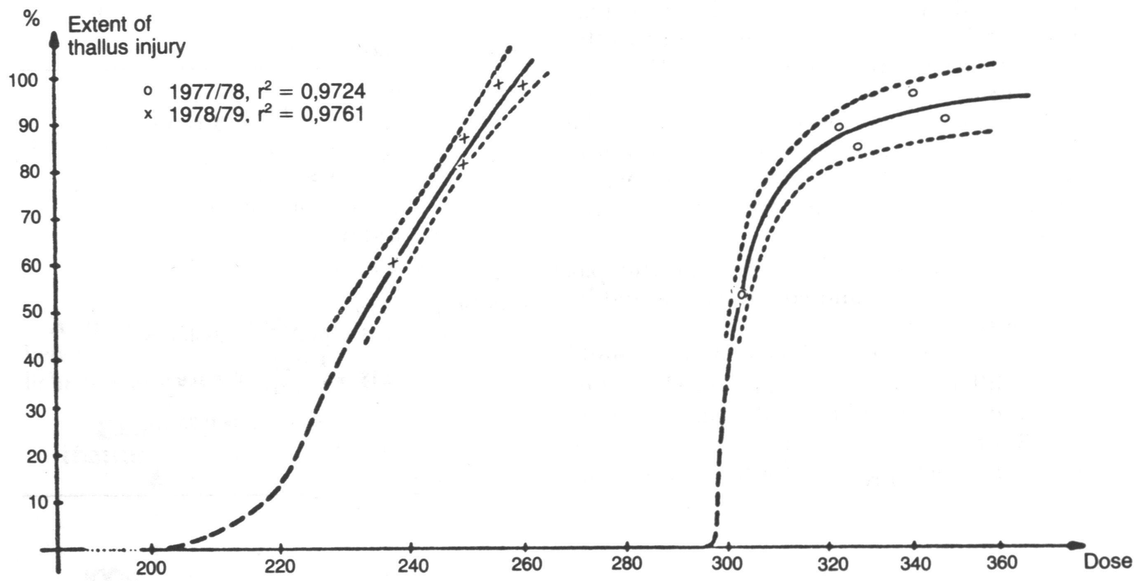

Fig. 3 Regression lines for the data in Table 1 fitted by eq. (7) and eq. (14).

DISCUSSION

The calculation of dosages and the suggested dose/injury relationship seems to fit the data very well ($r^2>0.97$) as expected from the number of parameters and observations. More important is the agreement between the estimated parameters for the two independent sets of observations.

A notable result is the very low value of q found (q_{mean} =0.12). This means that transplanted lichens – and possibly lichens in situ as well – to a very high degree are injured by the SO_2 *"level"* and not by fumigation episodes with high concentrations. This can be illustrated by doubling the time of exposure and concentration, respectively, in eq. (2).

$$(15) \qquad a = \frac{D_{2t}}{D_{2c}} = \frac{C_i^{0.12} \cdot 2 \cdot t}{(2 \cdot C_i)^{0.12} \cdot t} = 1.84$$

Doubling the exposure time gives about 84 % greater relevant dose than doubling the concentration.

The limiting levels for SO_2 for epiphytic in situ H. physodes were 90–110 $\mu g/m^3$ in Copenhagen (JOHNSON and SØCHTING, 1973) and 60–70 $\mu g/m^3$ in England and Wales (HAWKSWORT and ROSE 1970) as arithmetic winter averages. As shown in Table 3 threshold concentrations of 45–90 $\mu g/m^3$ are found with the mean value 70 $\mu g/m^3$. The threshold concentrations are of course varying considerably when threshold dose is kept constant. Only the dose contributions from concentrations between C_O and C_{max} are having an effect on the lichens. Using seasonal arithmetic means may therefore lead to misleading results in trying to set limiting levels for SO_2 for lichens.

There is one irregularity in Table 3, i.e. the upper asymptotic value for the winter 1978/79 of 258 %. This is nonsense of course, as the injury cannot exceed 100 %. For the winter 1977/78 the value is between 96–109 % which is the theoretical correct value. An explanation to this result is the greater sensitivity of the transplants to the SO_2 exposure during the winter of 1978/79 than during the winter of 1977/78; the slope of sensitivity b is 15 times greater and the threshold dose is lower. In 1978/79 at the two stations with the largest extent of thallus injury (VALB and GLAD) 68 % and 76 %, respectively, of the transplanted lichens were completely dead, while this percentage during 1977/78 was about 20 %. If dead lichens had been replaced by living ditto during the transplantation period the injury could have been more than 100 %. H. physodes were too sensitive in 1978/79 to be a suitable indicator at the most polluted localities when using a six month transplantation period, or the lichens at these stations have been influenced by other factors than SO_2.

The sensitivity of the lichens to SO_2 is closely dependent on their moisture status. Dried thalli survive high SO_2 concentrations in their surroundings without being damaged. The difference in sensitivity in the two year period should be explained by climatic factors. Table 4 shows some possible factors. The season 1978/79 was mostly wet.

Table 4. Some climatic factors in Copenhagen in the transplantation periods

Variable		1977–78	1978/79
Mean temperature	°C	2.8	1.4
Precipitation	mm	237	248
Mean relative air moisture	%	83	84
Number of days with rain, snow etc.	%	76	87

The main problem by making dose/response models is the reduction of the biological variability and the physiological properties of the thallus in relation to the environment to one factor for each period e.g. the slope of sensitivity. The degree of thallus injury is possibly the result of a stocastic process involving the probability of high moisture status of thallus and occurrence of high SO_2 concentrations. Perhaps this process is an explanation for the shown insensitivity for fumigation episodes.

REFERENCES

HAWKSWORTH, D. L. and ROSE, F. 1970. Qualitative Scale for estimating Sulphur Dioxide Air Pollution in England and Wales using Epiphytic Lichenns. Nature, 227: 145–148.

JOHNSEN, I. and SØCHTING, U. 1973. Influence of Air Pollution on the Epiphytic Lichen Vegetation and Bark Properties of Deciduous Trees in the Copenhagen Area. Oikos, 24: 344–351.

KROG, H. and BRANDT, N. 1975. Lav som indikatorplante ved studiet av luftforurensninger. NILU, Oslo.

MAGE, D. T. 1980 a. Frequency Distributions of hourly Wind Speed Measurements. Atm. Environ. 14: 367–374.

MAGE, D. T. 1980 b. The Statistical From for the Ambient Particulate Standard. Annual Arithmetic Mean VS Annual Geometric Mean. JAPCA 30 (7): 796–798.

RAMKÆR, K., JOHNSON, I. and SØCHTING, U. 1980. Biologisk monitering med lichener af SO_2-imissionen i Hirtshals-området. Report, Institute of Thallophytes, University of Copenhagen.

SØCHTING, U. and JOHNSEN, I. 1978. Lichen Transplants as Biological Indicators of SO_2 Air Pollution in Copenhagen. Bull. of Environ. Con. & Toxicology 0007-4861/78/0019-0001.