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Effects of atmospheric gases on terrestrial plants and critical levels of air pollution*

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Abstract — An integrated approach was developed to determine the critical levels of air pollution for ecological standard setting based on the unified index of biological response, by taking into account the effects of all pollution components simultaneously. An empirical model of plant productivity was taken as the dose response model for gaseous pollutant effect on the productivity of trees and the annual productivity of plants was used as the above mentioned index. The CO_2 increase in the lower atmosphere was considered to potentially increase plant productivity and NO_2 was estimated as neutral while being dangerous for plants as a chemical precursor of ozone or as a source of acidification. The maximum permissible chronic O_3 and SO_2 levels for trees were estimated and it was found that O_3 is much more phytotoxic, as compared to SO_2, with a rather narrow range of permissible levels (27–33 ppb) which complicates its monitoring and control.

Keywords: air pollution; biological responses; terrestrial plants.

Man-made air pollution causes significant changes in the atmosphere. It is not only a problem in cities and industrial centers but has also become a regional or even a global problem due to a long-range atmospheric transport. It is well-known that during the last two decades many woodstands in the USA and Europe were damaged heavily by this broad-scale environmental factor. Therefore, the problem of critical levels for air pollution (including its monitoring and control) is extremely urgent nowadays.

Many countries have implemented special national air quality standards to protect natural and managed ecosystems (Commission, 1986). At the international level, the United Nations Economic Commission for Europe (ECE) produced some expert reports and policy recommendations relevant to the problem of long-range transboundary air pollution (ECE, 1988).

At the initial stage, these expert considerations and subsequent recommendations were often based on: incomparable criteria for quantitative assessment of biological responses; "component-by-component" approach (e.g., critical levels for SO_2 were sometimes assumed to be ozone-independent).

This paper makes an attempt to develop an integrated approach to the problem based on

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the unified index of biological response.

INDEX FOR BIOLOGICAL RESPONSE ASSESSMENT

Unfortunately, contemporary knowledge is not sufficient to propose a proper index or multi-index of the ecosystem level which could reflect ecosystem structure and functions completely enough. Such proposals would not be effective because a generally accepted "dose-response" model for gaseous pollutant effect on the structure and functions of an ecosystem has not been produced yet by theoretical ecologists.

In such a situation it is expedient to use the simplest numerical index with the following properties: ecological significance; economic importance (for managed ecosystems); availability of a "dose-response" model for gaseous pollutant effects; availability of a sufficient database to estimate the parameters of this "dose-response" model. The proposal is to use the annual productivity of plants (annual net assimilation) as the above mentioned index.

CRITERION OF PERMISSIBLE CHANGES

Many atmospheric gases, in particular carbon dioxide, penetrate into the photosynthetic organs of plants via stomata and produce positive or negative effects on them. Since CO_2 plays a special role as one of the major initial substances required for photosynthesis, its growth in the lower atmosphere can potentially increase plant productivity.

As the level of CO_2 in the lower atmosphere has been increasing since the preindustrial times, there is a respective increase in plant productivity. F. N. Semevsky (USSR, Moscow, Natural Environment and Climate Monitoring Laboratory, 1988), suggested using this circumstance and proposed the following criterion of permissible pollution: the total negative effect of chronic concentrations of gaseous pollutants in the lower atmosphere (surface layer) should be less than the positive effect of CO_2 enrichment since the preindustrial times.

"DOSE-RESPONSE" MODEL

The following empirical model of plant productivity change was proposed earlier (Izrael, 1989):

$$P = P_0 \exp\left(\sum_{N=1}^{N_0} b_N \triangle D_N\right),$$

where P_0 and P are initial and altered productivities; N_0 — total amount of pollutants within the bunch under consideration; ΔD_N — change in the N-th pollutant dose; $b_1, \cdots, b_{N0}$ model parameters to be estimated. These parameters depend on plant group (trees, crops) and on production indices (total biomass of a plant or its part, or yield).

Estimation of parameters b_N can be carried out using the results of "dose-response" experiments and a special procedure of averaging.

Plant seeds, seedlings or cuttings usually serve as biological material for such experiments. They are cultivated in special chambers with known (constant or variable) concentrations of a gas under consideration. Since the effects of regional and global air pollution and CO_2 enrichment were of great practical interest during the last decades, the total amount of respective data presented in publications is quite sufficient for estimating the above-mentioned model parameters for CO_2 , O_3 , NO_2 and SO_2 . The output of the experiments was arranged as standardized blocks (Kunina, 1986; 1988):

$$D_{i1} < D_{i2} < \cdots < D_i R_i ;$$

$$B_{i1} , B_{i2} , \cdots < B_i n_i ,$$

where i — number of an experiment in the whole data array; n_i — number of various dose loads in the i-th experiment; D_{ij} and B_{ij} — values of the j-th dose and plant biomass (at the end of the i-th experiment), respectively.

The statistical procedure for estimating coefficients b_N (Izrael, 1989; 1990) was realized as a computer program. Some results of these computations for trees are presented in Table 1.

Table 1 Estimates of parameters *b* of the "dose–response" model for tree productivity, 10^{-3} ppm^{-1} h^{-1}

Gas	Estimate of *b*	Standard deviation	Degrees of freedom
CO_2	0.70×10^{3}	0.14×10^{-3}	21
O_3	−5.76	1.13	36
SO_2	−0.70	0.18	42
NO_2	−0.21	0.22	23

MAXIMUM PERMISSIBLE CHRONIC O_3 AND SO_2 LEVELS FOR TREES

The results presented above show that the direct effect of NO_2 on plant growth by penetration via stomata into needles/leaves is not significant (respective coefficient b is approximately equal to its standard deviation). However, nitrogen dioxide could be dangerous for plants, for instance, as a chemical precursor of ozone or as a source of acidification.

Taking into account direct effects only, the above-mentioned criterion ($P > P_0$) for the permissible levels of chronic O_3 and SO_2 pollution could be expressed quantitatively as follows:

$$\Delta = b\ (SO_2)\ \Delta\ D\ (SO_2) + b\ (O_3)\ \Delta\ D\ (O_3) + b\ (NO_2)\ \Delta\ D\ (NO_2) > 0,$$

where $\Delta\ D\ (.)$ — changes in the doses, and $b\ (.)$ — respective model coefficients (Table 1). However, coefficients $b(.)$ are available with some uncertainty (i.e. with errors). Thus, a stronger relationship than $\Delta > 0$ should be fulfilled to guarantee, at some confidence level, that the altered value of the productivity is not less than the initial one ($P > Po$). For instance, for the 0.95 confidence level the relation looks as $\Delta \geqslant 1.65\ \sigma\Delta$, where $\sigma\Delta$ is a standard deviation of Δ.

The permissible changes of O_3 and SO_2 chronic concentrations (as compared with the preindustrial levels) fulfilled in the last relationship are shown in the Fig. 1. When running the computation, CO_2 concentration increase since the preindustrial period was assumed to be 76.5 ppm (Shands, 1987).

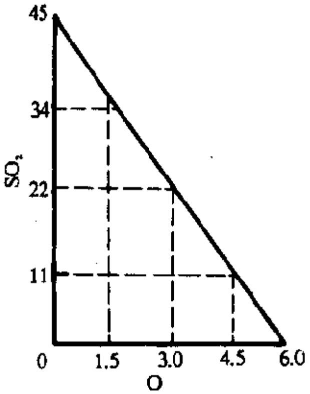

Fig. 1 Permissible range (inside the triangle) of changes in O_3 and SO_2 concentrations, ppb

It is rather difficult to estimate the preindustrial levels of SO_2 and O_3 in the lower atmosphere. To make the estimation one should create a comprehensive model for some key processes: emission, transfer and chemical transformations.

However, a sketchy estimation could be based on the current pollution levels in the "cleanest" regions. For instance, the estimate of the global background level is below 1 ppb for SO_2 and equals 27 ppb for O_3 (the latter was estimated by averaging the monitoring results from the South Pole Climate Station; Rovinsky, 1986).

Taking into account the last estimates of the preindustrial background O_3 and SO_2 levels and estimates of permissible changes (Fig. 1), the following critical chronic SO_2 concentrations can be proposed for large-scale (regional and global) air pollution (Table 2).

Table 2 Critical chronic concentrations for SO_2 large-scale air pollution

O_3,	ppb	27	28.5	30	31.5	33
SO_2,	ppb	45	34	22	11	0 (background level, < 1 ppb)

CONCLUSION

Ecological standard setting (critical level implementation) should not be carried out in a "component-by-component" manner (e.g., for SO_2 and O_3 separately). It is expedient to use an integrated approach, i.e., to take into account the effects of all components simultaneously.

It is advisable to use the integrated monitoring stations to observe current concentrations of gaseous pollutants. These stations provide a good opportunity to monitor not only the excess of one gas, but also dangerous changes of the whole bunch.

The direct effects of NO_2 could be estimated as neutral. Its ecological danger is related to other circumstances (e.g., NO_2 is a chemical precursor of O_3; NO_2 is one of the main sources of acidification).

O_3 is much more phytotoxic as compared to SO_2. Its permissible range is rather narrow

(27-33 ppb) which complicates its monitoring and control. Therefore, ozone is a problem of extreme importance.

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