Environmental Factsheet No. 6, 1995 (Updated May 1998)

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So much and no more

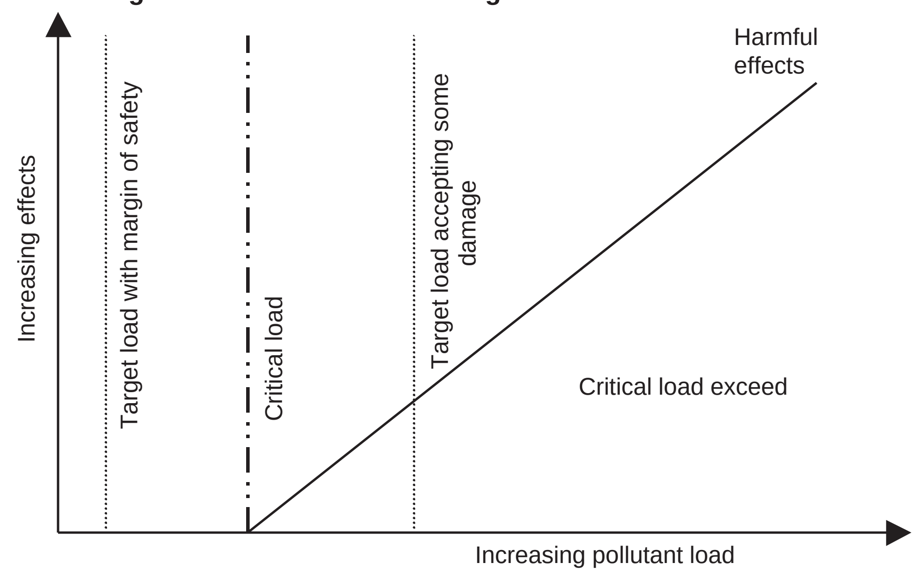
In order to determine the extent to which the emissions of air pollutants will have to be reduced, if the environment is to be protected from damage, it is essential to know the limits to nature's tolerance.

Critical loads

Various attempts have been made since the late 1970s to calculate the tolerable levels for acid deposition – later to become known as ”critical loads.” Then in 1986 an international scientific workshop on critical loads for sulphur and nitrogen produced this definition: ”The highest load that will not cause chemical changes leading to long-term harmful effects on the most sensitive ecological systems” (1).

It can be said that in a strict sense a critical load, according to that definition, is one that does not produce any effect on

Figure 1. Critical loads and target loads.



the most sensitive receptor even in the long term. Receptors may be individual species, types of soil, ecosystems, etc.

In 1988 the Convention on Long Range Transboundary Air Pollution (CLRTAP, see factsheet No. 3, April 1993) adopted the critical-load concept, making it basic to the future development of international agreements concerning limitation of the emissions of air pollutants. As work within the Convention has proceeded, various alternative definitions of a critical load have been tried, the most favoured one being: ”A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (2). As a definition this is however hardly satisfactory, since it allows too much room for interpretation.

Target loads

Also appearing in political negotiations aimed at the reduction of emissions is the term ”target load.” While determined essentially in accordance with the critical-load concept, target loads take other aspects into consideration as well, such as national environmental objectives. They may therefore be higher or lower than the critical loads, depending on the manner in which the situation is judged in different cases. They may be set lower, for instance, in order to leave a margin of safety, thus following a practice that is standard in the medical field. Target loads may on the other hand be allowed to be higher, which means in effect a deliberate acceptance of a certain degree of environmental damage, or risk of damage (see Figure 1). When set higher, they may be regarded as interim targets, reflecting the need for a stepwise approach to the reduction of emissions. In which case they should later be progressively reduced to a level at or below the critical load.

Scientific agreement

In the spring of 1988, two major international scientific conferences were held on the subject of critical loads. One was concerned with sulphur and nitrogen depositions (3), the other with atmospheric concentrations of gaseous pollutants (4). Later follow-up meetings included those in 1992 on nitrogen (5) and gaseous pollutants (6), two meetings in 1993, on effects on materials and on ozone (7), respectively, one in 1994 on nitrogen (8), and one in 1996 on ozone (9).

The conclusions from these various meetings are summarized below. (They can also be found in the so-called mapping manual (11).) It should be kept in mind, when considering them, that the proposed critical-load figures have always tended to be set successively lower as research methods improve and more data becomes available. It is thus not unlikely that today’s critical loads will also be revised downwards.

Acid deposition

The critical load for acid deposition will depend on the buffering capacity of the soil – on how quickly the minerals in the soil can be freed by weathering, and so enabled to neutralize the acid.

One effect of soil acidification is to impoverish the soil’s nutrient status, according as base cations, such as potassium, calcium, and magnesium, are leached out of it. This may in turn result in nutrient deficiencies and imbalances, which are thought to be among the causes of forest decline in Europe.

Another effect is to increase concentrations of potentially toxic metals, such as aluminium, in the soil water. This is especially the case when the pH of the mineral soil has fallen below 4.4. Increased soil-water concentrations of aluminium can produce damage to trees’ roots, and aluminium ions, when leached out into lakes and streams, can become transformed and so toxic to organisms such as fish.

In lakes and streams the biological effects of acidification can in any case be extensive. The diversity and number of aquatic species diminish, with greatly changed and impoverished ecosystems as a result.

Table 1 shows the critical loads for various types of soil, calculated a) for the total input of acid, and b) for a corresponding quantity of sulphur. By way of explanation, a kiloequivalent of hydrogen ions per square kilometre corresponds to 0.16 kg of sulphur per hectare. In any effort to protect a given area from acidification, the total acid input must however be taken into account. In the table the figures for sulphur assume sulphur to be the only cause of acidification. Should nitrogen also be a cause, the soil will be able to tolerate less sulphur than is there indicated. The limits will have to be lowered, too, if other acidifying processes, such as the removal of biomass in forestry operations, also have to be taken into consideration.

As regards forest soils, the critical load for sulphur in the most sensitive areas is at the most 3 kg per hectare per year. Since the critical loads for

Table 1. Critical loads of acid and sulphur in relation to the weathering capacity of forest soils.

	Minerals controlling weathering	Usual parent rock	Acid input (keq $H^+/km^2/yr$)	Sulphur deposition kg S/ha/yr)
1.	Quartz K-feldspar	Granite Quartzite	<20	<3
2.	Muscovite Plagioclase Biotite (<5%)	Granite Gneiss	20-50	3-8
3.	Biotite Amphibole (<5%)	Granodirite Greywakee Schist, Gabbro	50-100	8-16
4.	Pyroxene Epidote Olivine (<5%)	Gabbro Basalt	100-200	16-32
5.	Carbonates	Limestone	>200	>32

Source: Ref. (3)

surface waters and ground waters are usually determined by the sensitivity of the surrounding soils, they are often about the same for both. If the deposition is higher than the critical load, the system will suffer long-term acidification. From mapping it has appeared that in 1990, the critical depositions of sulphur were being exceeded over approximately 87 million hectares (representing 15 per cent of the area of sensitive ecosystems) in Europe.

The depositions of sulphur vary greatly however from one region to another in Europe. Where emissions are very great, as in parts of the Czech Republic, the deposition may reach 100 kg S/ha a year, as against 20-40 kg/ha in much of the rest of Central Europe. Whereas in the forest areas of southern Scandinavia the depositions may amount to 20-30 kg/ha, in the far north they are only about 3 kg/ha a year.

Eutrophication

Nitrogen can cause over-fertilization (eutrophication) as well as acidification of ecosystems. It is this dual effect that has made critical loads more difficult to define – than it is, for instance, if only the effects of sulphur have to be considered. Furthermore, the critical loads for nitrogen will depend on a variety of factors, including ecosystem productivity, the activity of microorganisms in the soil, and the composition of the vegetation.

Eutrophication is a frequent occurrence, since most terrestrial and some inshore ecosystems are nitrogen-limited and thus additional nitrogen coming into the system will be quickly taken up by organisms (plants, trees, plankton) and usually stimulate their growth. This commonly leads to ecosystem imbalances, in the form of changes in nutrition, competitive relationships, and resistance to insects, fungi, and stress from temperature and drought. These changes can almost all be regarded as adverse. Excess growth from eutrophication may also mean that more nutrients/base cations may be taken up by plants and trees, thus impoverishing and acidifying the soil still further.

Acidification occurs in soil when most of the system is saturated with excess nitrogen that can no longer be bound or retained by biological matter. Nitrogen in the form of nitrate (NO_3^-) will consequently leak from the system, taking with it nutrient (alkaline) base cations such as calcium and magnesium (Ca^{2+}, Mg^{2+}), and thus acidifying the soil. Acidification may also occur in non-saturated soils during winter when the vegetation is not taking up nutrients.

In terrestrial ecosystems the critical loads for nitrogen are usually defined with reference to forest soils, the intention being to preserve ecosystem stability in the long term, or at least

Table 2. Critical loads for nitrogen (kg N/hectare/year) to (semi-)natural terrestrial and wetland ecosystems. Source: Ref. (11).

	Critical load	Indication of exceedance
Trees and forest ecosystems		
Coniferous trees (acidic, low nutrition state)	10-15 ##	Nutrient imbalance
Coniferous trees (acidic, mod.-high nutrition state)	20-30 #	Nutrient imbalance
Deciduous trees	15-20 #	Nutrient imbalance; increased shoot/root ratio
Acidic coniferous forest	7-20 ##	Changes in ground flora and mykorrhizae;increased leaching
Acidic deciduous forests	10-20 #	Changes in ground flora and mykorrhizae
Calcareous forests	15-20 (#)	Changes in ground flora
Acidic forests*	7-15 (#)	Changes in ground flora and leaching
Forests in humid climates	5-10 (#)	Decline lichens and increase in free-living algae
Heathlands		
Lowland dry heathlands	15-20 ##	Transition from heather to grass; functional change (litter production; flowering; nitrogen accumulation
Lowland wet heathlands	17-22 #	Transition from heather to grass
Species-rich heath/acid grassland	10-15 #	Decline in sensitive species
Upland Calluna heaths	10-20 (#)	Decline in heather dominance, mosses and lichens; nitrogen accumulation
Arctic and alpine heaths*	5-15 (#)	Decline in lichens, mosses and evergreen dwarf shrubs
Species-rich grasslands		
Calcareous grasslands	15-35 #	Increased mineralization, N-accumulation and leaching; increase in tall grass, change in diversity**
Neutral-acid grasslands	20-30 #	Increase in tall grass, change in diversity
Montane-subalpine grasslands	10-15 (#)	Increase in tall graminoids, change in diversity
Wetlands		
Shallow soft-water bodies*	5-15 ##	Increase in tall graminoids, decline in diversity
Mesotrophic fens	20-35 #	Decrease typical mosses, increase in tall graminoids, nitrogen accumulation
Ombrotrophic bogs*	5-10 #	Decline in isoetid species

* Unmanaged, natural systems. ** Low end of the range for N limited, high end for P limited ecosystems.
Reliable. # Quite reliable (#) Expert judgement.

not to reduce the vitality of forest trees. Using the simple mass-balance approach, the critical load has been put between 3 and 20 kg N/ha/yr, according, among other factors, to whether the site is low productive or high productive. These figures are however probably too high, since they are based primarily on trees. If other vegetation also has to be considered, the critical load would probably have to be lower. For ”natural” forests, with no biomass removal, the critical load should be 2-5 kg/ha/yr.

In the case of freshwaters, the effects of acidification arising from nitrogen deposition are usually of greater importance than those from additions of nutrient. It has been shown that in some areas of Europe, nitrogen deposition contributes significantly to the acidification of freshwater systems – especially in areas where there is little or no vegetation surrounding the lakes and streams, as in parts of Norway, northern Britain, and some alpine regions.

The critical loads for eutrophication effects on semi-natural ecosystems are mainly based on observed changes in vegetation, such as alterations in the composition of species. Such observations are of course only possible after the critical load has been exceeded – and sometimes only after that has been going on for a long time. Such empirically derived data can therefore be said to represent an upper limit for the critical loads. In Table 2 the critical loads are either given in ranges or expressed as a ”less than” figure. This is because of the variation in sensitivity within the same type of ecosystem and/or the lack of data to enable a figure to be set for the upper limit. The critical loads of nitrogen for several types of ecosystem still have to be determined.

The average deposition of nitrogen over much of the Central European area is now 30-40 kg N/ha/yr. Over forest land in southern Sweden it is 20-30 kg/ha, and on coniferous forest in the Netherlands it may locally exceed 100 kilograms.

Gaseous forms

Instead of critical loads, the term critical levels is often used when speaking of gaseous pollutants. These have been defined as: ”The concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems or materials, may occur, according to present knowledge” (2).

Usually figures are given for one pollutant only. In fact however the air over Europe consists of a cocktail of substances, and it has long been known that in combination they can intensify each other’s effect (so-called synergism). Thus if the synergistic effects are to be taken into consideration, the critical levels should be lower.

Ozone

Crops are believed to be particularly sensitive to ozone (O_3), but at present concentrations forest trees may also be damaged. At the conference in 1988 (4) critical levels were agreed for each kind of pollutant, including ozone.

The 1992 workshop (6) saw the development of a new concept of critical levels for ozone – it now being expressed as cumulative exposure over a threshold concentration, using the formula: (x) ppb-hours above (y) ppb baseline (ppb=parts per billion: 1 ppb=2 $\mu g/m^3$). At a workshop in 1993 (7) the threshold level was set at 40 ppb (referred to as AOT40, accumulated exposure over a threshold of 40 ppb).

In respect of crops the critical level for ozone only relates to daylight hours during a three-month growing season, usually May-July. The long-term critical level has been set at an AOT40 value of 3000 ppb-hours, according to what is regarded as an ”acceptable” loss in yield. Experiments have shown that such an exposures may cause yield losses – which are signs of a chronic effect – of about 5 per cent. The critical levels for crops are derived primarily from the results of experiments with wheat.

Furthermore, a short-term critical level was set at AOT40 values of 200 or 500 ppb-hours (depending on humidity) accumulated over five consecutive days. If subjected to a higher exposure, sensitive species such as beans and clover may develop visible ozone injuries (show acute effects).

An AOT40 value of 10,000 ppb-hours has been proposed as a provisional critical level for forest trees. In this case the cumulative exposure should be calculated for daylight hours during a six month period commencing 1 April. It should apply to both broadleaf and coniferous trees.

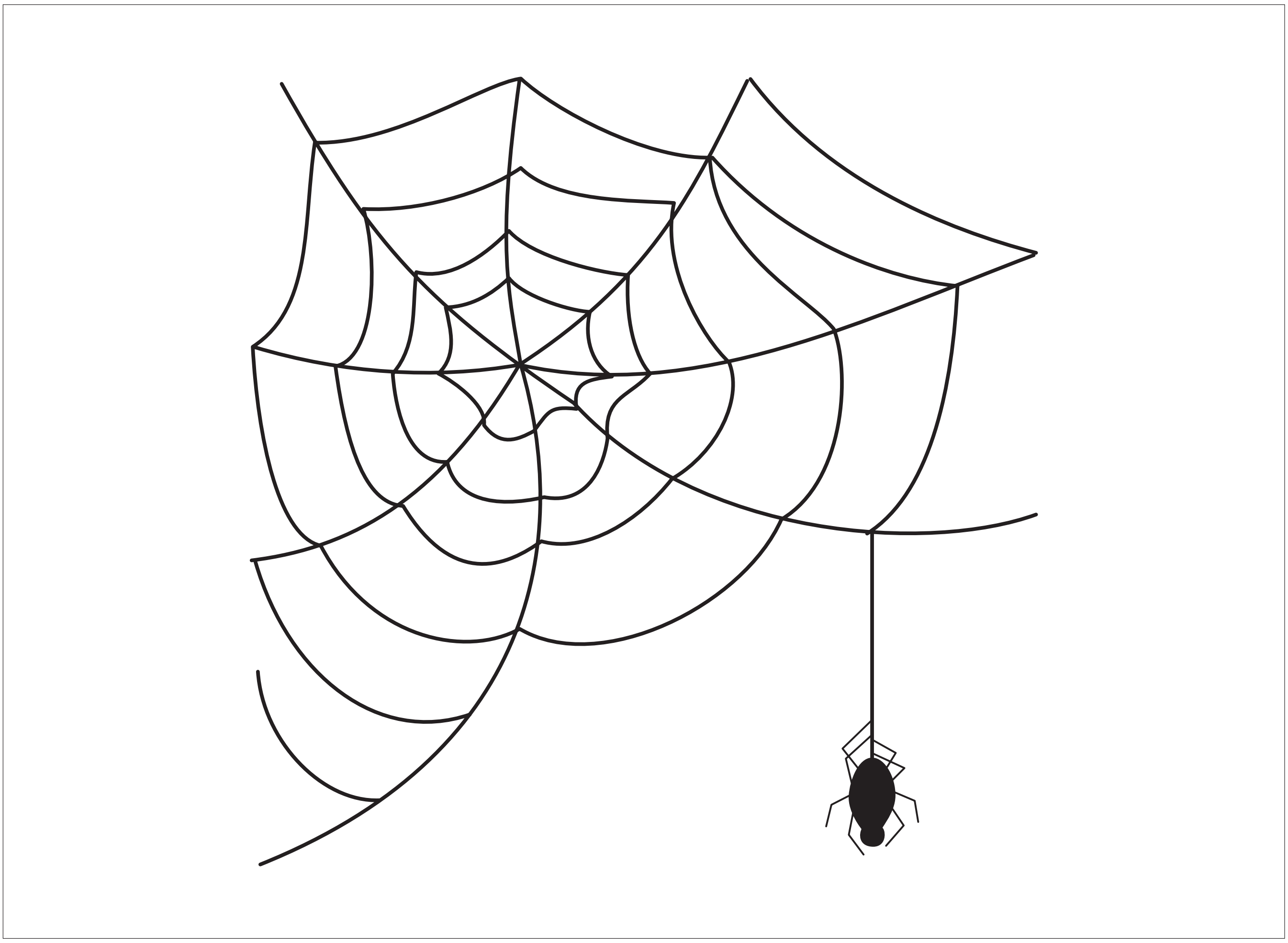
As regards ozone effects on natural and semi-natural plant communities, only limited data for some individual species are available. The effect of greatest concern are likely to be changes in the composition of species. Results from experiments suggest however that effects may occur at values of AOT40 similar to the critical level for crops, i.e. above 3000 ppb-hours. Therefore, this critical level should be applied also to semi-natural vegetation.

Ozone is formed in the troposphere as a result of reactions between nitrogen oxides and volatile organic compounds (VOCs) in the presence of sunlight. Monitoring data shows that the critical levels given above are being exceeded over almost the whole of Europe. For example, in the period 1985-87, the ”old” one-hour critical level of 150 micrograms per cubic metre ($\mu g/m^3$) was shown to be exceeded at about 75 per cent of the measuring stations in western Europe. The ”old” eight-hour and the seasonal mean critical levels were exceeded at all of the stations (10). Computer modelling has shown that a reduction of at least 75 per cent of the emissions both of nitrogen oxides and VOCs will be needed if critical concentrations are not to be exceeded.

Sulphur dioxide

The atmospheric concentrations of sulphur dioxide (SO_2) that are critical for forest ecosystems and natural vegetation have been put at 10-20 $\mu g/m^3$ both as an annual mean and a half-year (October-March) mean. For agricultural crops the critical level is 30 $\mu g/m^3$ both for annual and half-year means. The most sensitive species are believed to be certain lichens, which may be damaged at annual means as low as 10 $\mu g/m^3$.

In some parts of Europe, particularly the eastern and central, these



critical levels are being greatly exceeded.

Nitrogen oxides
Nitrogen oxides (NO_x) are generally regarded as less toxic to plants than sulphur dioxide and ozone. Because of its relatively low toxicity, no critical levels have been set for NO_x alone, but only in combination with O_3 and SO_2, assuming that the concentrations of the two latter pollutants are each below the critical levels noted above. The aim of the critical levels defined for NO_x is to protect the structure and functioning of the plant community. The maximum annual mean for NO_x (NO and NO_2 added together and expressed as NO_2) would then be 30 $\mu g/m^3$ and the peak level 95 $\mu g/m^3$ (average 4-hour exposure). These levels are likely to be exceeded only in urban areas or their vicinity.

Ammonia
Direct damage from ammonia (NH_3) occurs primarily in farming areas with intensive stock-keeping. The yearly, monthly, 24-hour, and hourly mean values for critical concentrations are 8, 23, 270 and 3300 $\mu g/m^3$.

Effects on materials
The deterioration of materials caused by atmospheric pollution is a cumulative and irreversible process, although some deterioration may take place even in the absence of pollutants. It has been proposed, in discussion of the possible critical levels, to define an ”acceptable rate of deterioration” which would be linked to pollution values (11). No such rate has been agreed, but it has been suggested that for trial purposes values between 1.2 and 2 times the rate of corrosion in pristine areas could be used.

Provisional dose-response functions for a number of materials, such as carbon steel, zinc, copper, and limestone, exist for sulphur dioxide. By using data on the annual mean SO_2 concentration, the rates of deterioration at different sites and for various types of material can be calculated, and areas where the acceptable rate of deterioration is exceeded identified. For each such mapping unit, the SO_2 concentration that would keep this rate at an acceptable level – the critical level – can then be calculated.

The impact of ozone on organic materials, such as rubber, pigments, and various polymers, was also considered, and a provisional critical level of 20 ppb as an annual mean has been chosen.

Mapping of critical loads
Mapping of critical loads for air pollutants goes steadily on. The maps are used particularly when international agreements are being negotiated for reducing emissions of sulphur and nitrogen oxides. European maps showing the critical loads for acid depositions and eutrophying nitrogen depositions as well as critical levels for ground-level ozone, have been produced by the Coordination Center for Effects in the Netherlands (12).

The data on which the maps are based derives principally from the individual reports of some twenty countries, which are printed separately in an annex to the report. Standard methods for the actual mapping were developed by the Task Force on Mapping of the Convention on Long

Range Transboundary Air Pollution, and is presented in a report (11). Where national data is lacking, European data is used for assessing the critical loads and levels.

The critical load for acid deposition equals to the amount of acid – expressed as acid equivalents per hectare per year – that can be absorbed by the soil without causing harmful long-term effects on the ecosystems. From the Coordination Center's maps it appears that it is the northern and central parts of Europe that are especially sensitive to acid deposition. A considerable part of the European ecosystems falls, too, into the most sensitive category – in other words, can at the most withstand a deposition of 200 acid equivalents per hectare per year (eq/ha/yr). In terms of sulphur, that amounts to 3.2 kilograms S/ha/yr.

The critical loads data have been aggregated to 150 x 150 km grid squares by constructing cumulative distributions of critical loads for the ecosystems within each grid square. All the Center's maps are on a 5 percentile basis, which means that if the input of acid (or nitrogen, in maps for eutrophication) does not exceed the amount indicated by the square's colour, 95 per cent of the ecosystems within that grid cell will be safe from acidification/eutrophication.

By comparing data on the ecosystems' sensitivity with data on the depositions of acidic pollutants, maps can be obtained which show where and by how much the critical loads are being exceeded – and so give information as to how much depositions, in other words emissions, need to be reduced.

What is required

A drastic reduction in emissions of air pollutants is urgently needed if the environment is not to be further damaged. In order to stop the ongoing deterioration, concentrations and depositions of air pollutants will have to be brought down to below the critical loads.

More than twenty European environmentalist organizations have, on the basis of up-to-date and internationally agreed scientific data on critical loads, agreed on the following as objectives in regard to the overall emissions of air pollutants in Europe (13):

❒ at least a 90 per cent reduction in emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x);
❒ at least a 75 per cent reduction in emissions of volatile organic compounds (VOCs) and ammonia (NH_3);
❒ at least a 75 per cent reduction in concentrations of tropospheric ozone, to be achieved by meeting the objectives for NO_x and VOCs as above.

The reductions are based on the emission levels in the early 1980s and refer to western and eastern Europe, including the European part of Russia.

These are minimum demands, but they do not necessarily imply that every country or region must achieve equal reductions. In areas with very high emissions, greater reductions will be necessary, while in some other areas the reductions may be allowed to be lower.

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