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Batterman, S.

IIASA Working Paper

WP-90-067

November 1990

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Foreword

IIASA's Regional Acidification INformation and Simulation (RAINS) model is being extensively used within the framework of the UN Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. In particular, it is providing scientific guidance in the development of new protocols for reducing sulfur and nitrogen emissions which lead to regional acidification of the environment. Using source-receptor relationships from a meteorological model, and the relative costs of reducing emissions in one country versus that in another country, it can calculate the country-by-country emission reductions that will reduce deposition in a given target receptor region to a specified value. However, how should one specify the target regions and the target deposition? Should we try to reduce deposition everywhere, or must we give up on protecting the environment in some very sensitive areas? This paper deals with the sort of compromises that a policy-maker has to face.

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Abstract

This paper addresses the use of critical loads in optimized emission abatement strategies. As deposition targets, critical loads can not be satisfied at all receptors. In Europe, consequently, there is a need for alternative criteria which still relate to ecological indicators, yet which are feasible, consistent and equitable. Two criteria are suggested: the relative critical load coverage, and the relative deposition reduction. These criteria permit deposition goals to be set which guarantee that a specified fraction of ecosystems will attain critical loads, and thus be protected from adverse environmental impacts. In areas which can not achieve critical loads with the best available control measures, deposition is reduced to a specified fraction of the unabated level.

After presenting examples which demonstrate their derivation, strengths and weakness of these criteria are discussed. The criteria have been implemented in the RAINS optimization model. Some preliminary examples show the sensitivity, interactions and utility of the criteria. Results obtained indicate that optimized emission strategies based on critical loads are similar to emission strategies based on deposition reductions, at certain levels of the criteria. This suggests that it may not be necessary to utilize critical loads to formulate deposition targets. A second example shows the effect of excluding countries from European cost minimization. A country's participation can save costs with moderate deposition targets, however, significant costs can be imposed with low (stringent) deposition targets. These preliminary results have significant implications for negotiations and multilateral negotiations. Suggestions for future analyses conclude the paper.

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Optimized Abatement Strategies Using Critical Loads: Suggested Deposition Criteria and Results

*Stuart Batterman**

1 Introduction

1.1 Organization

This paper discusses approaches for setting deposition targets in optimized emission control strategies which are based on critical loads. This paper is in four sections. Section 1 provides an overview of several issues related to emission control strategies which are ecologically-based. Section 2 outlines the modeling approach. As an illustration, simple examples based on typical deposition scenarios and critical load distributions for a single receptor are given. The suggested approach has been implemented and tested in the RAINS model. Three examples and results are presented in Section 3. Conclusions and suggestions for future work are presented in Section 4.

1.2 The RAINS model and optimization framework

The optimization mode of the Regional Acidification Information and Simulation (RAINS) model (Alcamo et al., 1990) permits the identification of control strategies which meet specified deposition goals. Calculated results are 'optimal' as defined using a single criterion, e.g., minimization of total European abatement costs, and subject to specified emission and deposition constraints. Strengths and limitations of such receptor-based or targeted optimization methodologies for integrated scale models are the subject of several papers (e.g., Amann, 1989; Batterman and Amann, 1990). Here, the RAINS-OPT framework is used with deposition targets which are ecologically-based and which permit a high degree of flexibility.

1.3 Critical loads

Considerable work has gone into developing the notion of critical loads, defined by the Skokloster Critical Load Workshop (Nilsson and Grennfelt, 1988) as:

> ... "quantitative estimate of exposure to one or more pollutants below which harmful effects which are judged to be significant on specific elements of the environment do not occur according to present knowledge".

Thus, attainment of critical loads should protect ecosystems against both short and long-term damage from pollutants. In the RAINS model, critical loads can serve as deposition targets in the optimization mode, or as indirect indicators of impact potential by comparison with deposition levels in the scenario analysis mode.

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The idea of a deposition threshold below which damage will not occur is extremely attractive, due both to its relevance and its simplicity. However, the threshold nature of critical loads can be problematical for several reasons:

1. The rate and nature of physical processes such as soil acidification occur along a continuum. Criteria such as compliance or exceedence with thresholds do not indicate the severity or rate of ecological effects. Moreover, the attainment of critical loads may not be sufficient to prevent adverse impacts. Other factors, e.g., deposition of certain cations, may require consideration and additional constraints.

2. To be useful, comparisons between predicted deposition and critical loads require that model predictions be largely free from absolute bias. In general, model performance is better when outputs are examined in a relative manner, e.g., using correlations, then in an absolute manner. The importance of absolute bias in model predictions may increase as emissions are reduced due to the role of biogenic and unattributed anthropogenic emissions, i.e., 'background' contributions of atmospheric long-range Transport models.

3. No information is given about the confidence of results. For example, both critical loads and model predictions can be regarded as probability density functions which can be convoluted to yield the certainty that the true critical load will be achieved.

Despite these reservations, critical loads can be useful in formulating and evaluating control strategies, as currently being done in negotiation efforts aimed at deriving target deposition strategies for Europe.

2 Suggested modeling approach

The suggested approach to using critical loads in optimized control strategies separates the problem into two components. The first component directly addresses environmental goals and utilizes maps of critical loads. The second component is more subjective in recognizing technical limitations, political constraints and uncertainty. Together, these components form two criteria used to set deposition targets in the optimization problem:

1. Fraction of ecosystem which meets the critical load, computed from the ecosystem area in which it is technically feasible to meet the critical load. This is called the *relative critical load coverage* (RCLC) criterion. It can be considered the relative percentile of the critical load distribution.

2. Fraction achieved of the potential deposition reduction which is technically possible. This is called the *relative deposition reduction* (RDR) criterion.

These criteria provide a flexible and hopefully equitable means of incorporating ecologically-based deposition criteria into optimized strategies. The choices of the RCLC and RDR parameters remain subjective (or political) preferences. The criteria can be used in addition to other deposition constraints (e.g., on the maximum deposition) and policy constraints (e.g., minimum country-specific reductions) already existing in RAINS-OPT. This paper provides an in-depth discussion and analysis of the new criteria. First, two definitions are made.

Potentially attainable areas (PAA) are regions where it is technically feasible to achieve critical loads. Thus, the total acidic deposition in these areas, resulting when sulfur, nitrogen and ammonia controls are fully employed throughout Europe, is below or equal to the critical load specified for the area. In contrast to PAAs, *nonattainable areas* (NA) cannot achieve critical loads under any realistic, technologically feasible scenario.

The area falling into PAA and NA areas is computed at the highest resolution available. While it is possible that all of an EMEP grid cell is a potentially attainable area (or conversely a nonattainable area), most cells contain both attainable and nonattainable areas. Using the Chadwick and Kuylenstierna (1990) critical load classification and the maximum technologically possible emission reductions, an average of 65.4% of each grid cell can attain the critical load and thus is a PAA. An average of 14.8% of each EMEP grid cells is a nonattainable area. (The remainder, 19.2% of the grid cell, is not classified, e.g. water surfaces.) Critical loads can be attained in only a few of the EMEP grid cells (when existing N deposition is also taken into account); thus most cells contain nonattainable areas, as well as potentially attainable areas.

Ideally, critical loads should be achieved in all areas. It is clear, however, that this cannot be accomplished in NAs. What then is a reasonable goal for these areas? The criteria suggested in this paper help handle the dichotomy presented by attainable and nonattainable areas.

2.1 Critical loads in potentially attainable areas: relative critical load coverage criterion

Critical loads describe the maximum tolerable acidic deposition, a limit based on microscale features, e.g., soil depth, soil composition, precipitation, elevation, etc. The spatial resolution of the critical load mapping effort is of practical concern. In RAINS, the grid resolution for critical loads is about 150 by 150 km. Such large areas may be heterogeneous with a broad distribution of critical loads. Thus, critical load mapping efforts provide the frequency distribution of different sensitivities. Fig. 1 shows a hypothetical example of the distribution, employing the sensitivity classes used by Chadwick and Kuylenstierna (1990). In this example, deposition below 0.32 g S/m^2-yr is necessary to protect all areas within the grid cell. However, only 5% of the area is in the most sensitive (0.32-0.64 g S/m^2-yr) class. Thus, 95% of the area could be protected by keeping deposition at the limit of the next most sensitive class, namely, 0.64 g S/m^2-yr.

The cumulative frequency distribution shows the area protected (i.e., percentage under its critical load) as a function of deposition, as depicted in Fig. 2. Mathematically, the fraction A of land satisfying critical loads given deposition level s is

$$A(s) = \int_o^s f(s)ds = F(s) \qquad (1)$$

where f(s) is the distribution (probability density function) of the critical loads and F(s) is the cumulative frequency distribution. The deposition target corresponding to the spatial coverage fraction A is given by the inverse of the cumulative frequency distribution.

$$s = F^{-1}(A) \qquad (2)$$

For simplicity, Eq. (2) is implemented using a linear interpolation within deposition classes. The highest deposition class is interpolated between its lower limit (5.12 g S/m^2-yr) and twice this value. (The Chadwick and Kuylenstierna critical load classes use geometric steps.) Reading from Fig. 2, 50% of the area is protected by a deposition of 2 g S/m^2-yr.

The suggested criterion sets critical loads based on the desired spatial coverage. The criterion is called the *relative critical load coverage* (RCLC). It is relative since only those areas which can achieve the critical load are considered (as discussed in Section 2.2). The RCLC criterion is equivalent to the same percentile of the critical load distribution.

There are several points to be made concerning the RCLC criterion in optimization:

1. The deposition target is non-linear with spatial coverage (the problem, however, remains in the standard linear problem formulation).

2. There is no reward to reducing deposition until the highest critical load is reached (e.g., 10.5 g S/m^2-yr in Fig. 2).

3. There is no point in reducing deposition below the point where the critical load has been reached in all areas (0.32 g S/m^2-yr in Fig. 2).

4. Finally, a small fraction of the EMEP grid cell can greatly influence results of the optimization. (More is said on this point in Section 2.3.)

An interesting and important aspect of the RCLC criteria is that it applies to every grid cell (if all European receptors are selected). This avoids the geographic conflicts that would result if the area satisfying the critical loads is maximized. In contrast, if the area which attains the critical load was maximized (subject to budget and other constraints), a highly inequitable distribution of benefits would result. For example, critical loads would not be attained in many northern and central European countries. The RCLC is more equitable as the benefit is extended to every EMEP grid cell. (This discussion raises the question of scale dependence. The 150 x 150 km size of the EMEP grid may be a reasonable compromise between detail and diversity for this indicator, but this could pose an issue for countries which are much smaller or much larger than this size. For example, if only one cell encompassed all of Europe, the RCLC criterion is equivalent to maximizing the area satisfying critical loads!)

A second aspect of the RCLC criterion is its use as an output or indicator. Although not currently implemented into RAINS, this could be accomplished easily and provide the average (relative) coverage of critical loads by country, or by receptor.

The use of critical loads to set deposition limits which specify the fraction of protected ecosystems is legitimate if several conditions are satisfied:

1. Ecosystem sensitivity is independent of modeling biases. To a first degree, this condition is surely violated. For example, precipitation generally increases with elevation, so high elevation areas are likely to receive more wet deposition. Also, high elevation soils are often coarse and poorly buffered, thus these soils will have lower critical loads. Other instances of model bias may exist. These problems are inherently connected to the spatial resolution of the model. With fine resolution, the problem disappears. As suggested in Section 4, this area is ripe for investigation.

2. Decision makers don't care which of the ecosystems are protected within the grid cell. As the preceding example suggests, deposition of 2 g S/m^2-yr will protect half of the ecosystems in the grid cells. Higher elevations, e.g., mountain tops, may not be protected. It is unlikely that the decision maker will be happy if the most visible portion of the forest is destroyed. Again, this is a question of spatial resolution in the model.

3. The critical load calculations are accurate. The use of critical loads to set deposition limits permits little margin for error. In the hypothetical example (and the map of Chadwick and Kuylenstierna), the smallest deposition interval is only 0.32 g S/m^2-yr. Model uncertainty will tend to decrease the area which is protected at a given deposition. Said differently, total confidence that the critical loads will protect ecosystems would lower the critical load.

4. The criterion is applied and interpreted fairly. Model misuse can be a problem in any circumstance. However, the suggested criterion is sophisticated, and some model users may have trouble understanding the implications.

Other objections to using critical loads as deposition targets will no doubt be found. The author suspects that most objections will be related to scientific issues (especially copollutants), valuation issues, model errors and uncertainty (especially data base needs) of critical loads.

2.2 Deposition targets in nonattainable areas: relative deposition reduction criterion

The practicality of using critical loads to design abatement strategies is an important issue. As Amann (1989) has demonstrated, using even the best available technology throughout Europe at a cost exceeding 100 billion D.M. annually will not produce depositions which meet critical loads at all European locations. This occurs since (natural) 'background' deposition provides an uncontrollable yet significant deposition, technological options are limited, and critical loads may be small. A deposition reduction (from current levels) of 90% or more is insufficient for some receptors, e.g., those situated in central Europe.

Since critical loads can't always be achieved, deposition targets for NAs must utilize additional information. Nonattainable areas are widespread in Europe, comprising a portion of nearly all the EMEP grid cells used in RAINS-OPT (when N deposition is taken into account). Simply not setting targets for these locations is a bad idea, since some of these areas may have severe impacts from acidic deposition. The suggested criterion is the deposition reduction relative to the maximum reduction possible. For each receptor in a NA, then, the relative deposition reduction (RDR) is calculated as:

$$RDR(\%) = \frac{D_{current} - D_{future}}{D_{current} - D_{minimum}} \times 100\% \tag{3}$$

where $D_{current}$ is the current deposition (or deposition resulting from current reduction plans), $D_{minimum}$ is deposition resulting from using the best available technology, and D_{future} is the deposition at some future time. Since current and minimum depositions at each receptor vary, deposition reductions are scaled differently at each receptor. While the RDR variable does not indicate the severity of environment impacts, it should relate to environmental improvement since the RDR criterion is only defined for depositions above the critical load.

As an example, Fig. 3 uses the same hypothetical distribution of critical loads discussed earlier. The current, unabated deposition is 14 g S/m^2-yr. Deposition can be reduced to 1.28 g S/m^2-yr using all available emission controls. The RDR variable is defined from 0 to 100% between these limits, as indicated in the figure. A 50% RDR specification corresponds to a deposition target of 7.6 S/m^2-yr.

Nonattainable areas have been defined as the portion of a EMEP grid cell which cannot attain critical loads. Most grid cells contain both nonattainable and potentially attainable areas. If both areas exist in a grid cell, then two criteria can be specified: the relative deposition reduction (RDR) in the NA, and the relative critical load coverage (RCLC) in the PAA. For example, Fig. 3 shows the relative critical load coverage (RCLC), defined for the PAA in the grid cell, as a function of deposition. The critical load is attainable in 70% of the grid cell. A 50% coverage goal would set a deposition target of 3.2 S/m^2-yr. This deposition would meet the critical load in 35% (50% goal x 70% attainable) of the total area in the grid cell.

2.3 Other issues

The two criteria, relative coverage of critical loads (RCCL) in potentially attainable areas, and relative deposition reduction (RDR) in nonattainable areas, have several common features:

1. Range of the criteria. By design, both criteria have a range of 0 to 100% at all receptors. This range is feasible at all receptors. If the grid cell contains an area which is not attainable, then both criteria can be used, and 100% of either criteria correspond to the same deposition target, the minimum deposition level technically possible.

2. Type of criteria. If the more stringent of the two targets is taken, the two criteria result in a single deposition target for the grid cell. This is desirable from the standpoint of the optimization, as the criteria provide a target deposition.

3. Outliers/robustness. Both indicators can be highly influenced by small areas, e.g., 1% of the ecosystems, in the EMEP grid cell. In the example, 100% ecosystem coverage required a deposition target of 0.32 g S/m^2-yr. If 95% coverage was sufficient, a limit twice this value would suffice. A similar problem affects the RDR criterion. As an example, assume that critical loads are given by Fig. 1 and that the minimum feasible deposition is

0.64 g S/m^2-yr. In this case, only 5% of the grid cell is unattainable. The RDR criterion is defined with respect to this small area. To minimize the influence of small areas in setting levels of the RDR and RCLC criteria, two variables are introduced to provide limits on the minimum area within the cell that is considered for the two criteria. Suggested limits are 5%. (Note: RAINS-OPT permits these exemptions to be specified for all of Europe or by country, and uses a default of 5%.)

4. Flexibility. At this point, the deposition target at each receptor is specified by two primary parameters: (1) relative coverage of critical loads for ecosystems which can attain critical loads by technological means; and (2) relative deposition reduction for ecosystems which cannot attain critical loads. Two secondary parameters are also used: (3) percent area exempted for attainable areas; (4) percent area exempted for nonattainable ecosystems. These parameters be selected on a receptor-, country- or European-wide basis. (Note: the program permits these parameters to be specified for all of Europe or by country.)

5. Other acid forming emissions. The critical load is a quantity which includes all deposition sources of acid forming matter, including sulfate, nitrate and ammonia. These three chemical species must be considered jointly in terms of their acidifying potential. There are several ways to do this. The preferred approach would convert the three pollutants to hydrogen ion (H^+) equivalents and employ a joint optimization using the three pollutants. (Joint sulfur and nitrogen optimization programs for RAINS-OPT are under development.) An alternative, less desirable, approach would reduce the critical load by the existing or predicted deposition of nitrogen and ammonia. (Note: The current approach reduces the critical load by the predicted nitrogen deposition, after conversion to sulfur equivalents. Nitrogen deposition is based on predictions employing the current nitrogen reduction plans.)

6. Cost function influence. Both criterion are defined in part using the maximum emission abatement technically possible. In RAINS-OPT, this abatement level is derived from the cost functions, which in turn are obtained from the energy submodule which uses engineering estimates of the potentials of current technology applied to the energy scenario of interest. In the future, additional abatement may be possible with developments in the efficiency of the best currently available control technology, or the emergence of new technologies which permit higher removals. Clearly, increased removal potential would permit more area to satisfy critical loads, thus changing the relative proportion between potentially attainable and nonattainable areas. Also, deposition targets would decrease as minimum technically feasible deposition decreases.

   From one perspective, the economic or technological factors on the emission side should not influence deposition targets based on ecosystem impacts. However, to have any practical value, such targets must be cognizant of technical limits. We should note that all optimized strategies (except removal minimizations without technical constraints) share this flaw.

7. Base emissions. A final issue concerns base emissions used for the RDR variable. Many countries have announced emission reductions which will be achieved at some future date, termed 'current reduction plans'.

   The RDR criterion can use any emissions as the unabated emissions. Using current reduction plans as base emissions will result in more stringent deposition limits than if the current (1986) emissions are used. (Note: as a default, the RAINS-OPT program reads a file containing the current reduction plans, and uses these emissions.)

3 Results

The examples and results presented in this section should be viewed as methodological examples. Their primary purpose is to provide a sensitivity analysis and demonstration of model capabilities.

Results use the critical load maps compiled by the Stockholm Environmental Institute at York (Chadwick and Kuylenstierna, 1990). This is a preliminary classification of ecosystem sensitivity. Work is underway to provide more complete critical load data. The critical loads are adjusted for nitrogen deposition, based on current reduction plans for nitrogen emissions (to be implemented by year 2000). The effects of ammonia are ignored. Unless otherwise specified, all model runs use 5% exclusion criteria, current reduction plans (in setting the RDR parameter) and optimize sulfur emissions using a minimum cost objective.

3.1 Sensitivity to area exclusions

A series of model runs were made to test the sensitivity of results to the secondary parameters, the exclusion of small ecosystem areas. Figs. 4 and 5 show the difference in total European costs when 0 and 5% (the default) of ecosystem areas are excluded. Both figures utilize all European receptors as targets. Fig. 4 shows the relationship between cost and the relative critical load coverage. Control costs rise sharply as high coverage is required, given the increasing costs of sulfur removal. The difference between 0 and 5% exclusion is typically 10-15%. This difference occurs since more stringent deposition targets are needed if no areas are excluded. Differences are smaller in the case of relative deposition reduction (Fig. 5). In this case, setting the exclusion parameter to 5% removed 259 grid cells (of 463 available). Results were similar as the 204 remaining grid cells tightly constrained results.

3.2 Interaction of RCLC and RDR parameters

A series of model runs is used to explore interactions between the criteria and draw some preliminary conclusions. Fig. 6 shows total European costs for various combinations of RCLC and RDR criteria applied to all European areas. In each grid cell, RCLC criteria apply where critical loads can be attained (i.e., PAA), while RDR hold where critical loads can not be attained (i.e., NA). Each line represents a constant level of the RDR criterion. For example, the top line represents a RDR of 75%. The midpoint of this line represents a RDR of 75% and a RCLC of 50%. The European cost to solve these two sets of deposition constraints (RDR=RCLC=50%) is about 38 billion D.M.

At high levels of RCLC (>90%), all lines converge since deposition targets converge. The key feature of the figure is the point at which the lines separate. Consider the right-most convergence point (at 90% RCLC). For 90% coverage of the critical loads, varying the relative deposition reduction parameter between 0 and 75% has little effect since deposition constraints set by the RCLC criteria are more stringent (at most receptors) than those set by the RDR criteria. Said differently, the relative deposition reduction must be set above 75% to form deposition targets more stringent that those produced by the 90% RCLC criterion. Similar results occur where the lower pair of lines diverge (at 75% RCLC). Here, the RDR must be above 50% to produce deposition criteria more stringent than those set by a 75% RCLC criterion.

The interpretation of Fig. 6 is important. If a 50% deposition reduction (in addition to current reduction plans) is achieved, then critical loads are satisfied for at least 75% of the ecosystems in every EMEP grid cell. If a 75% deposition reduction is achieved, then loads are met in at least 90% of the ecosystems. Critical loads will not influence optimization results unless a higher percentage of area is specified in the RCLC criterion. This also means that the two criteria are to an extent redundant. Although the exact relationship between the parameters isn't known, it is clear that high deposition (or emission) reductions will achieve critical loads over a large area.

3.3 Multilateral negotiation and pay-offs

Game theory approaches to emission abatement strategies have been suggested for some time. Information necessary for these approaches include pay-off matrices which detail the benefit for each player of a set of decision alternatives. Similar information is helpful in realizing multilateral agreements for technical assistance, pollution abatement, etc. A simple example is used to demonstrate the derivation of this information using RAINS-OPT.

The example attempts to define the value of having countries participate in optimized abatement strategies. Full participation of all European countries has been implicitly assumed in previous results. In reality, countries may be reluctant to participate because of the costs of pollution abatement. At the same time, these countries hope to reap the benefits of emission reductions by other countries. This constitutes the classical 'free rider' problem. Here, the benefit of having a single country participate in a receptor-based strategy is calculated. In the example, a country's participation involves two aspects: (1) willingness to reduce and pay for emission reductions; and (2) inclusion of that country's ecosystems in the receptor targets.

The availability of inexpensive pollutant abatement options in a country may benefit neighboring countries since emission reductions can be accomplished inexpensively, and since benefits occur in many countries due to long range transport of emissions. Thus we might expect that overall costs will decrease by participation. On the other hand, participation also means that additional deposition targets must be satisfied, which may impose additional costs. Either factor may be controlling.

Deposition goals throughout Europe are set using the relative critical load coverage and relative deposition reduction criteria. Two levels are used: RCLC=RDR=50% and RCLC=RDR=75%. Referring to Fig. 6, the points defined by these criteria are to the left of the convergence points, and thus the RDR criteria is controlling in both cases. Czechoslovakia is selected as the example country. Costs are computed without the participation of Czechoslovakia by keeping its emissions at unabated levels and by excluding Czech receptors. Optimization results are presented in Table 1.

In the case of moderate deposition goals (RCLC=RDR=50%), Czech participation provides a net value, i.e., a reduction in total costs, of 380 million D.M. to the European community. This occurs as inexpensive emission abatement potential in this country can meet Czech targets. This pollution abatement also benefits surrounding countries. Given widespread acceptance of these deposition criteria (and international cooperation), these results imply that it would be worth paying Czechoslovakia up to 380 million D.M. In contrast, more stringent deposition goals (RCLC=RDR=75%) impose a net cost of 2,200 million D.M. to the European community. This occurs as Czech deposition requirements require emission reductions in surrounding countries. In this case, theory unrealistically suggests that funds should flow out of Czechoslovakia to help accomplish Czech deposition goals.

The key points of the example are that (1) it is easy to compute the value of participation in a coalition, and (2) this value depends strongly on the deposition targets. This makes game-theoretic approaches considerably more complicated than has been previously recognized.

3.4 Binding receptors and computation aspects

Deposition targets which use the RCLC and especially the RDR criteria can produce an irregular deposition pattern. Based on results obtained in the using these patterns, targets at a large number of receptors may be binding. As an example, setting the RDR parameter to 75% resulted in the solution being constrained by 99 receptors (after the filters in RAINS-OPT which eliminate duplicate, non-binding, and non-dominant receptors were employed). This is in sharp contrast to optimizations which reduce the peak deposition in Europe, for example. Here, typically only a few receptor locations are binding. Because of this sensitivity, an optimization approach which ensures global optimality is needed to use the RDR and RCLC criteria. The LP solver in RAINS-OPT performs satisfactorily in this respect.

4 Discussion and conclusions

4.1 Discussion

Two new criteria for setting deposition targets in optimized emission abatement strategies have been developed and demonstrated. The relative critical load coverage criterion permits a minimum area to be specified in each grid cell in which critical loads will be attained, thus protecting the specified fraction of ecosystems. This measure is applied to the fraction of the grid cell which can meet the critical loads by available technical emission controls. The fraction which can not meet the grid cell is not disregarded — rather a second criteria, relative deposition reduction, is used to specify the deposition reduction relative to what is technically possible. The stricter deposition limit applies.

These criteria are motivated by a need to introduce ecological aspects in optimized control strategies. This is not a trivial matter since critical limits are not easily achievable. The new criteria permit great flexibility in setting deposition constraints in the RAINS-OPT model. These criteria can be used in addition to other deposition constraints, e.g., reduction of peak deposition levels, policy constraints, e.g., minimum or maximum percentage emission reductions, or other factors.

Deposition constraints can be set in a multitude of ways, and no specific approach is necessarily superior given uncertainties, decision-maker's preferences, etc. What has been demonstrated here is the convergence between relative deposition reductions and attainment of critical loads. Preliminary results indicate that protection of a specific fraction of ecosystems, say 50%, is equivalent to a uniform percentage reductions in deposition, say 75%, when reductions are allocated in an cost-efficient manner. If this is true, we might focus more on deposition reductions, which are easier to formulate and measure, than on critical loads. The physical mechanisms for this result is not surprising: there is a relationship between the amount of land which experiences depositions over the critical load, and high emission areas which have significant opportunity for abatements. More simply, critical loads are exceeded where there are uncontrolled or poorly controlled emission sources which influence deposition. These sources require abatement and tend to be selected no matter which deposition criteria is selected. Obviously, these simple statements do not deal with the subtleties of the problem, but they do offer some explanations. More investigation is needed, however. As suggested in the next section, results of alternative deposition criteria should be compared.

4.2 Future research

Results presented are tentative for a number of reasons. Foremost among them is the use of a preliminary map of critical loads. The analysis should be repeated when the improved map becomes available. No regional effects or country-specific impacts have been investigated, nor has any comparison been made with other types of deposition targets. The need for a comparison of strategies based on RCLC and RDR criteria with those based on flat rate reductions, minimization of peak deposition, or other criteria has been mentioned.

The new measures can also be used as indicators of the performance of emission abatement strategies. In particular, the relative critical load coverage criterion can be aggregated at any level. It would be informative to show maps indicating the amount of land satisfying the critical loads. The same information could be provided on a country basis (e.g., by averaging the resulting RCLC of receptors in the country). This display would be easy to incorporate into RAINS-OPT. This would also help to address the issue of scale dependence of the criteria.

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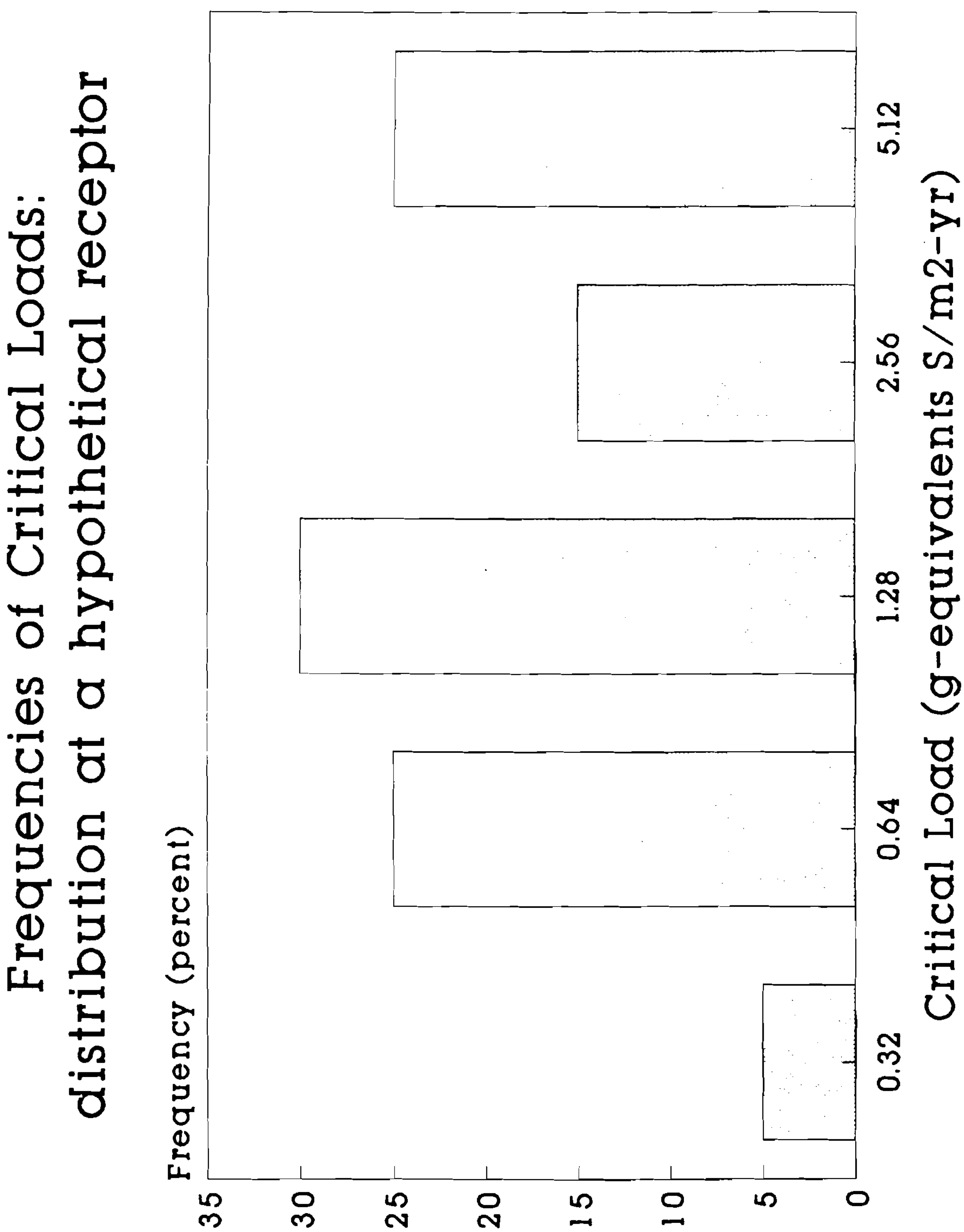

Figure 1: Distribution of critical loads at a receptor: hypothetical case.

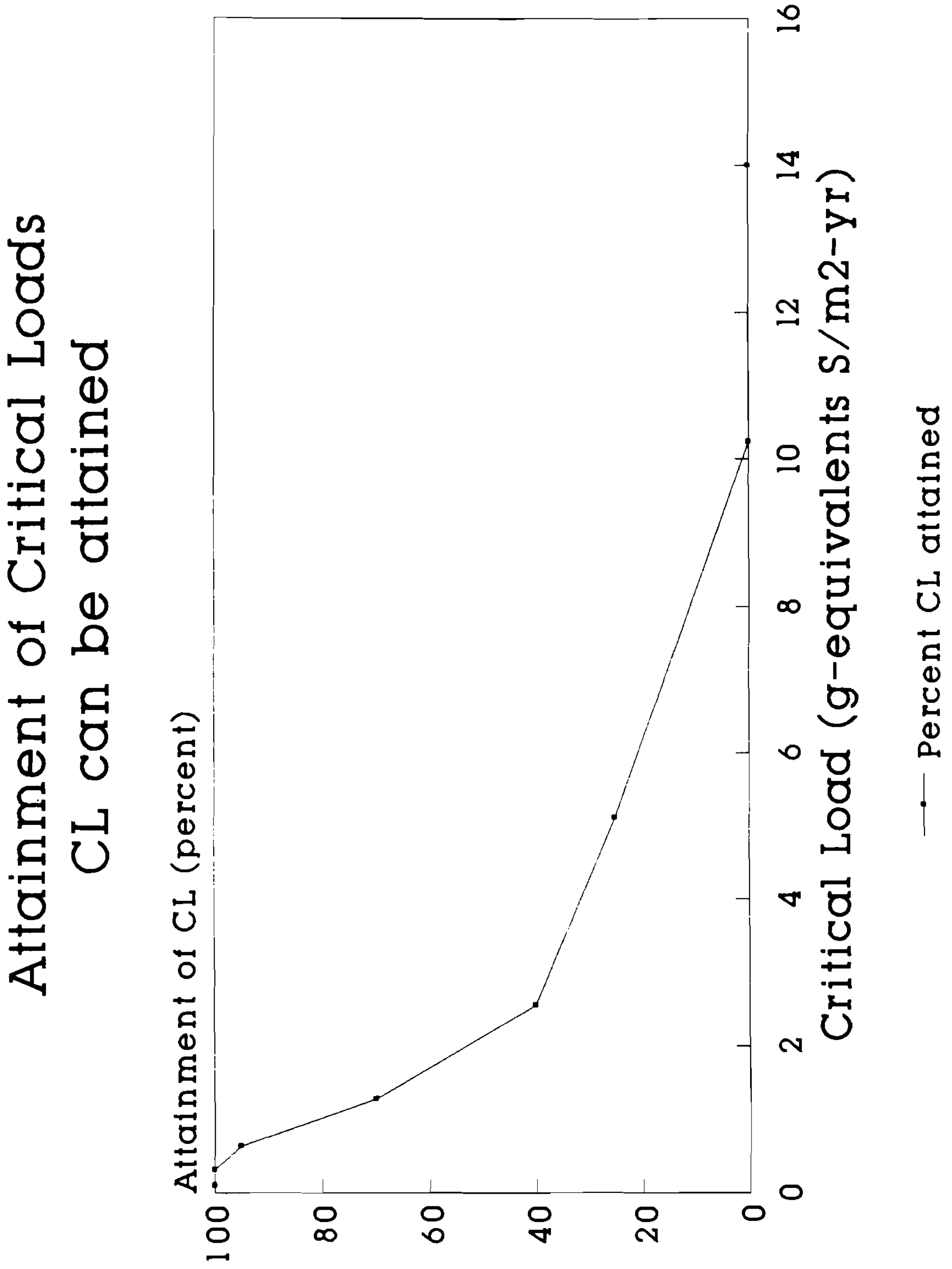

Figure 2: Attainment of critical loads as function of deposition target (using critical load distribution in Fig. 1).

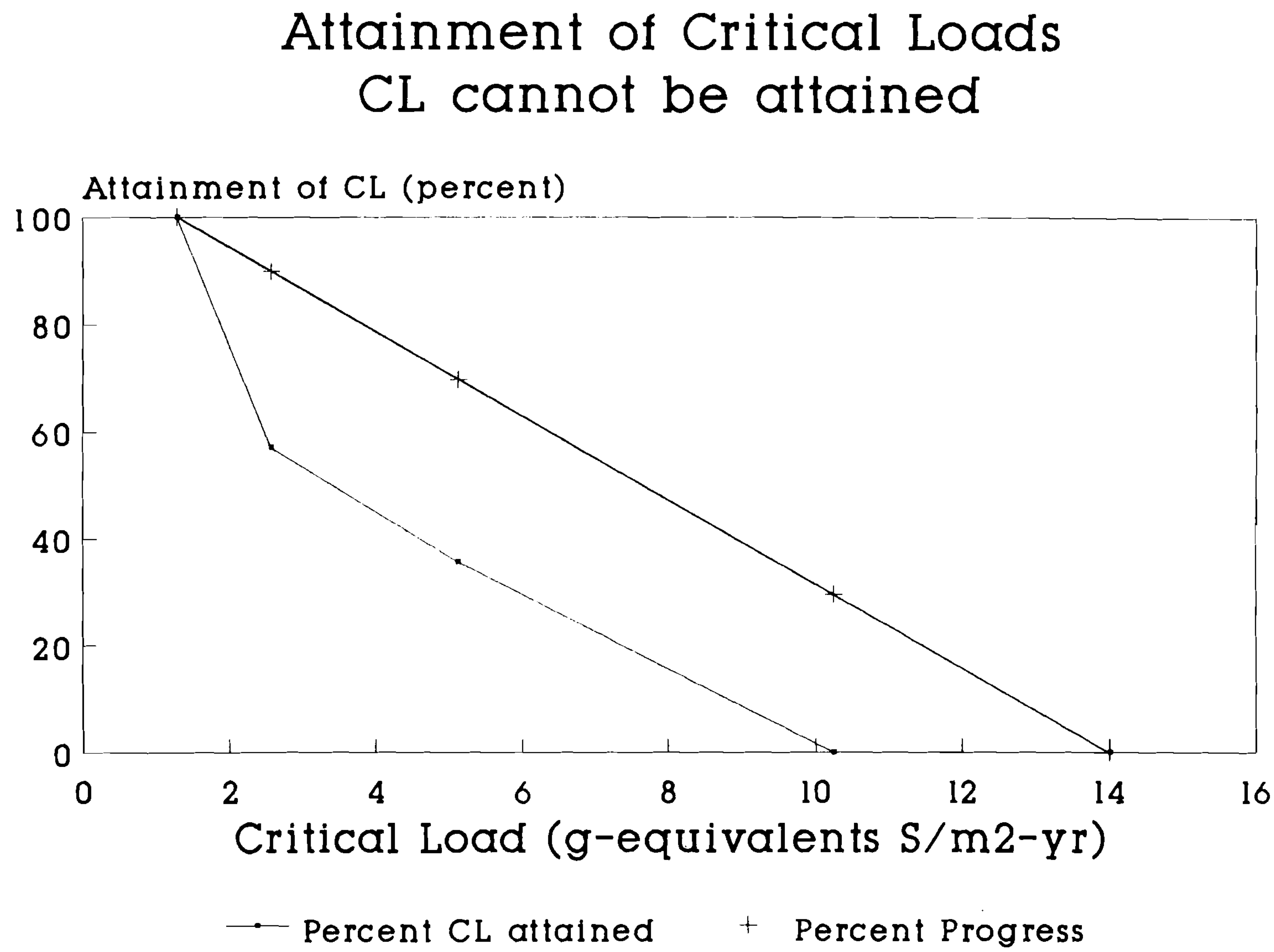

Figure 3: Relative coverage of critical loads and deposition reduction criteria as function of deposition target (using critical load distribution in Fig. 1).

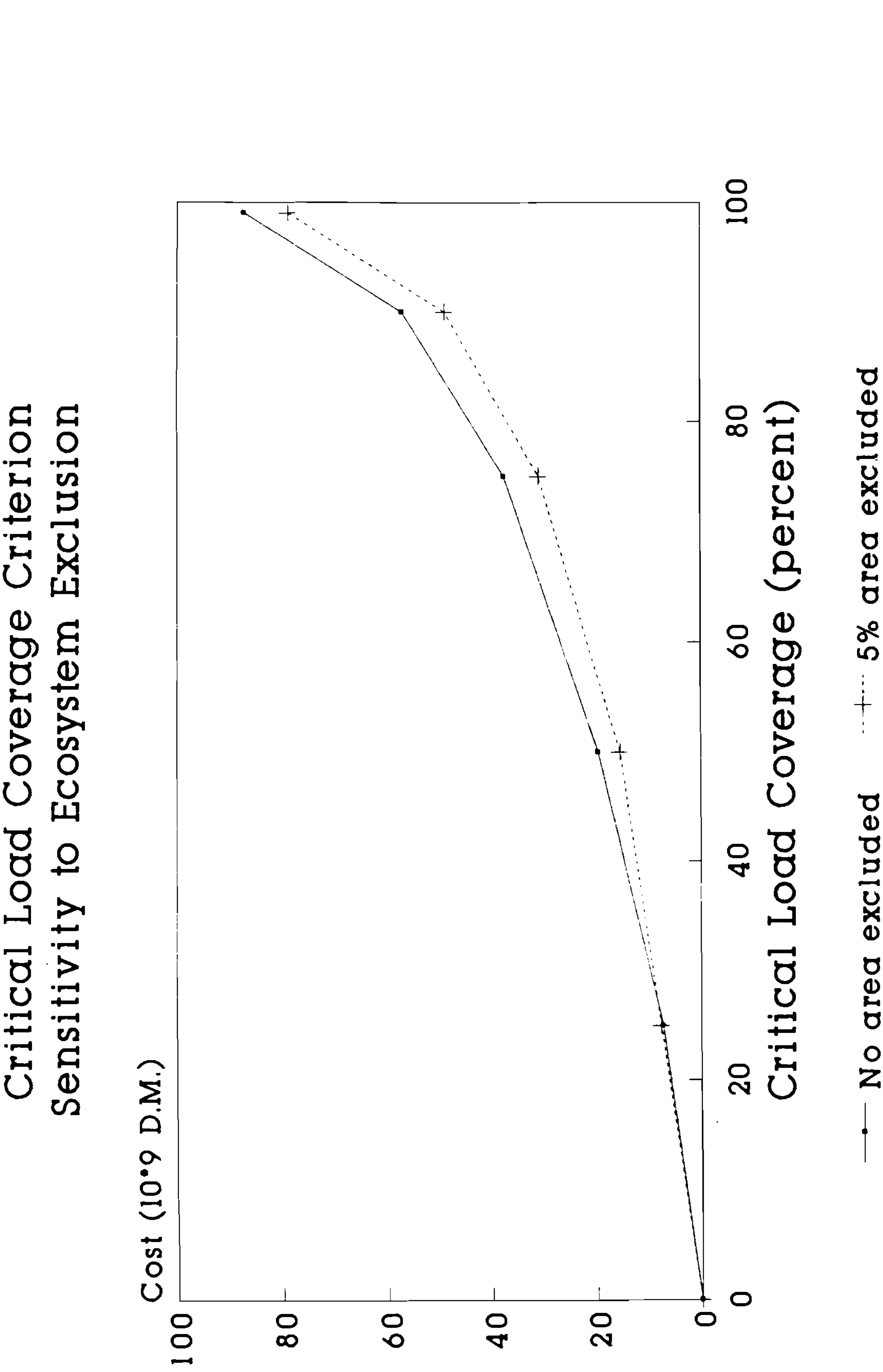

Figure 4: Total European control costs as function of relative coverage of critical load. Lines contrast results with no ecosystems excluded and with 5% of ecosystems excluded.

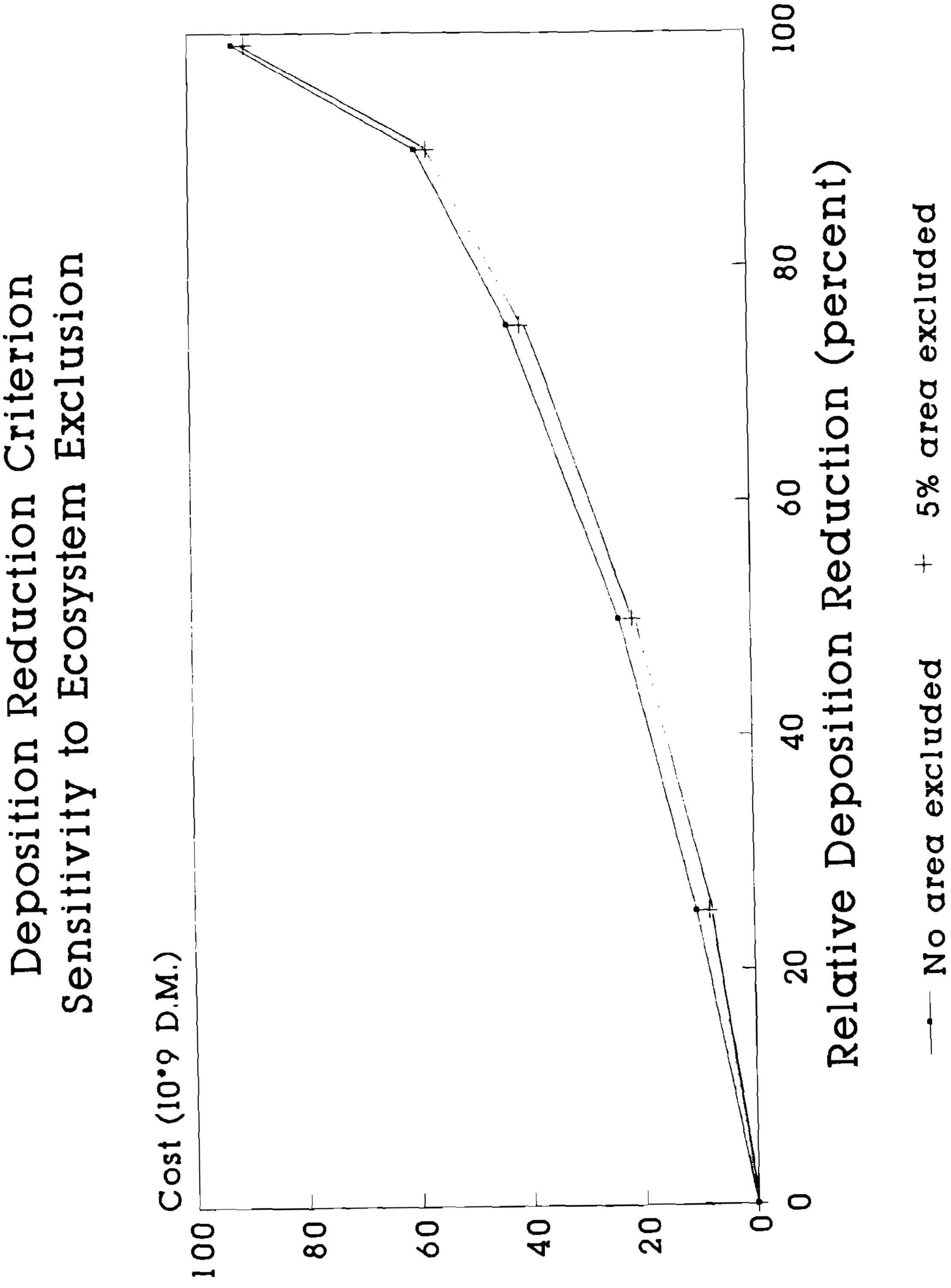

Figure 5: Total European control costs as function of relative deposition reduction. Lines contrast results with no ecosystems excluded and with 5% of ecosystems excluded.

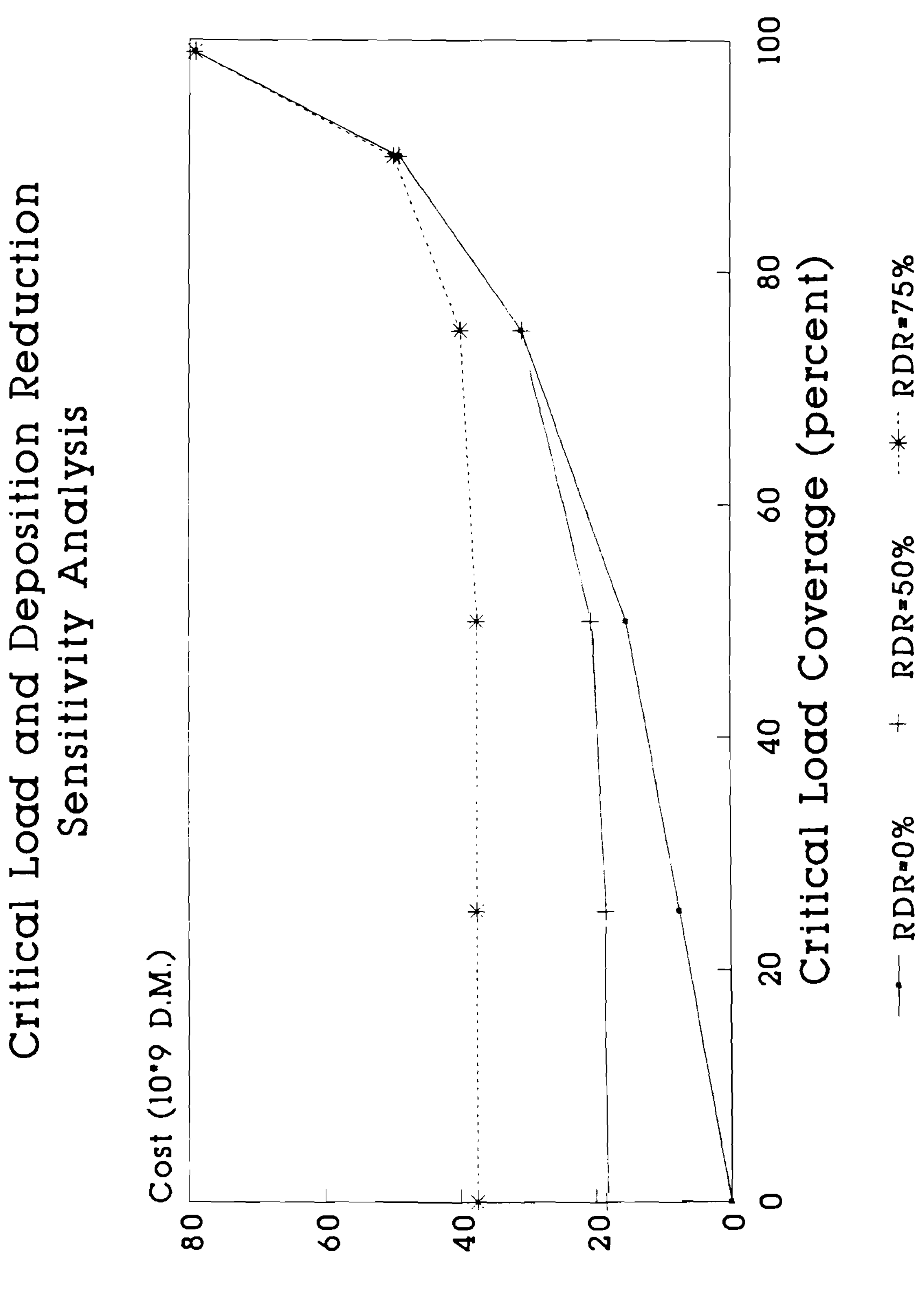

Figure 6: Total European control costs as function of two deposition criteria.

Table 1: Costs and benefits of Czechoslovakian participation in optimized European abatement strategy.

Case 1: RCLC=50; RDR=50

	Costs in 109 D.M.		
	Full Participation	No Participation	Value of Participation
Total European costs	20.67	20.29	0.38
Czechoslovakian costs	1.52	0.0	-1.52

Case 2: RCLC=75; RDR=75

	Costs in 109 D.M.		
	Full Participation	No Participation	Value of Participation
Total European costs	39.97	42.17	-2.20
Czechoslovakia costs	1.52	0.0	-1.52