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The CARMEN Status Report 1995

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Abstract

Progress in the EUROMOD project (RIVM no. 461501) is reported.
The EUROMOD project aims at the realization of a computer model that may support international negotiations concerning Europe's environment. The model is called CARMEN: *CAuse effect Relation Model for Environmental policy Negotiations*. CARMEN contains the results of many RIVM efforts in the building of databases and models.

We have implemented a chain of models that describe the fate of nitrogen emissions to the environment, either in the form of exhaust, sewage water, or fertilizer application. It is now possible to project the efficacy of abatement strategies at regional scales, such as river catchment areas and coastal seas.

Summary

Recent RIVM publications, like the GLOBE report, have contributed to European conferences on environmental and public health issues (Dobrice 1991, Lucern 1993). It is our aim to supply subsequent conferences with an interactive simulation model. RIVM will produce a computer model called CARMEN: CAuse effect Relation Model for Environmental policy Negotiations. Intentionally, the model is capable of incorporating (expert) modules from other institutes.

Many environmental issues interact with each other and it is therefore useful to consider more than one issue simultaneously, thus affording a better insight into the efficiency of abatement policies. CARMEN is an integrated assessment tool that allows the simultaneous analysis of several environmental issues from sources to effects. It shows the connection between pressure and impact in the form of socio-economic developments, local emissions - caused by unsound industrial, agricultural, or domestic practices - and pollution problems and their ecological and public health consequences.

This report describes the progress made in implementating the emission model, the atmospheric transport model, the soil and groundwater model, and the surface water model. Figure 1.3 displays the current status. Acidification of soils and eutrophication of rivers and coastal seas are fully described. Urban air quality and intoxication by heavy metals and persistent organic pollutants will be included in the near future. In order to allow abatement strategies to be optimized, one must have an overview of all economic aspects, including the cost of policy measures and the social costs of the damage, that will occur if no precautions are taken.

As an example of the sort of integrated assessment that CARMEN can make, we present a study of the eutrophication issue in European rivers and coastal seas. Figure 6.1 shows a diagram of the organization of the nitrogen model. We report the sensitivity of the coastal seas to the current abatement strategy. The analysis was performed for three coastal seas: the Baltic Sea, the North Sea, and the Sea of Azov.

Samenvatting.

Recente RIVM publikaties, zoals het GLOBE rapport, hebben een bijdrage geleverd aan het succes van Europese conferenties over milieu- en volksgezondheid aspecten (Dobrice 1991, Luzern 1993). Het is ons doel om de volgende conferenties te ondersteunen met een interaktief simulatie model. Het RIVM ontwikkelt daartoe het computer-model CARMEN: CAuse effect Relation Model for Environmental policy Negotiations. Het model kan in principe ook worden uitgebreid met deelmodellen van andere instituten.

Veel van de milieu-thema's zijn onlosmakelijk met elkaar verbonden en het is daarom bij de analyse nuttig om meer dan één thema tegelijkertijd te beschouwen. Op die manier kan een beter inzicht worden verkregen in de efficiëntie van de beleidsmaatregelen, die worden genomen om milieuproblemen te bestrijden. CARMEN is een geïntegreerd model dat de gebruiker de mogelijkheid biedt om simultaan de invloed van beleidsmaatregelen op verscheidene milieu-thema's van bron tot effekt te evalueren. Het model maakt op kwantitatieve wijze de verbinding tussen de druk op het milieu en haar gevolgen in een analyse van socio-economische ontwikkelingen, van lokale emissies, van milieu-problemen en van de gevolgen voor de ecologie en de volksgezondheid.

Dit rapport beschrijft de voortgang die geboekt is met het samenstellen van het CARMEN-model. Er is nu een emissie-model, een atmosferisch transport-model, een bodem- en grondwater-model, en een oppervlakte-wateren-model geïmplementeerd. Figuur 1.3 geeft een overzicht van de huidige status. De verzuring van bodems en de vermesting van rivieren en kustzeëen zijn volledig beschreven. De luchtkwaliteit in de grote Europese steden en de verspreiding van zware metalen en persistente organische stoffen zullen in de nabije toekomst aan het model worden toegevoegd. Om beleidsmaatregelen te kunnen optimaliseren, is het eerst nodig een goed overzicht van alle economische aspecten te krijgen. Dit houdt niet alleen de kosten van beleidsmaatregelen in, maar ook de sociale kosten van de schade die opgetreden zou zijn, indien er geen voorzorgmaatregelen genomen zouden zijn.

Als een voorbeeld van de analyse, die met het CARMEN-model gemaakt kan worden, wordt in het zesde hoofdstuk de vermesting van Europese rivieren en kustzeëen behandeld. Figuur 6.1 is een diagram van de opbouw van het stikstof-verspreidingsmodel in CARMEN. We rapporteren de gevolgen voor de kustzeëen van de huidige beleidsmaatregelen. De analyse werd uitgevoerd voor drie kustzeëen: de Oostzee, de Noordzee, en de Zee van Azov.

1. Introduction.

Rising demographic and economic pressures are threatening the European environment. These pressures persist because local socio-economic considerations are often allocated a higher priority than the immediate abatement of environmental problems. But some pollutants disperse over great distances and these problems may therefore become apparent far from the source, which increases the need for various parties to find a common solution. Some progress has been made in Europe towards a common abatement strategy. In this respect the work of the Convention on Long-Range Transboundary Air Pollution under the UN ECE on acidification is a good example. Still, many continental and global issues remain to be solved.

Policy responses, such as abatement strategies, can be regarded as an answer to impacts, which themselves are caused by increased pressures (see Figure 1.1). The state of the environment is the most easily observed of the four depicted elements, but does not always offer a key to solutions to the problems. In order to examine solutions one needs to clarify the connection between pressure and impact. The pressures are formed by local emissions caused, among other factors, by unsound industrial, agricultural and domestic practices. The impacts here are ecological and public health consequences, as well as loss of economic functions such as the drinking water supply. Figure 1.2, adapted from Grennfelt et al. (1993), illustrates the connection between several main sources, chemical compounds, effects and receptors. The pathways between pressure and impact are clearly entangled.

Two factors veil this connection. On the one hand, environmental impacts often lag behind their inputs. Such serious delays and corresponding political negligence may cause irremediable damage. On the other hand, pollution may be transported over long distances and need not necessarily affect the environment around its original source. To reduce pollutant emissions at source, it is necessary that regional decision makers negotiate with each other, since only a commonly implemented abatement policy can lead to solutions. To be cost-efficient, these policies should primarily aim at 'hot spots'.

Abatement policies for a single issue will generally affect other issues. For example, the reduction of traffic emissions will reduce both nitrous oxide and lead concentrations. It will also curtail acidification, eutrophication and heavy metal pollution. However, the reduction of sulphur oxide emissions has both positive and negative effects. It reduces the acidification of lakes in Northern Europe, and it cuts down the corrosion of building materials in Southern Europe. But at the same time, it leads to less aerosol formation. Aerosols have a high albedo and therefore reflect direct solar radiation. So a decrease in aerosol formation has an adverse effect on climate change. Because of these interactions, it is necessary to consider more than one issue at a time to gain insight into the efficiency of abatement policies. The need to find a common solution defines a complex problem, governed by conflicting social, economic and environmental interests on a continental scale.

Numerical computer simulations that assess the impact of proposed policies can help to inform these negotiations. A successful example of how to assess an environmental problem with the aid of computer simulations is the abatement of CFCs under the Montreal Protocol (UNEP, 1987) and its subsequent amendments in London (1990) and Copenhagen (1992). CFC abatement however is a single-social-interest-group, single-compound, single-environmental-issue problem. Complex problems, by contrast, can only be solved by negotiation between various European authorities. The negotiations may profit from an integrated approach, because an emission reduction developed for the abatement of one issue may have benefits for other issues, too. The most cost-effective abatement strategy can be found by relating abatement costs to the impacts on the environment.

Integrated Environmental Assessment at RIVM.

In 1991 the GLOBE-Europe organisation commissioned RIVM, together with other Dutch institutes, to study the integration of a number of environmental problems by presenting projections based on two contrasting scenarios of the socio-economic driving forces (RIVM, 1992). Also, the World Bank and OECD asked for an integrated assessment (Bollen et al, 1993) for the preparation of the 'Environmental Action Programme for Central and Eastern Europe'. The intense effort needed to carry out these studies, even with so few parties involved, prompted a project to integrate the various models and databases used in one single model. RIVM is developing this model, called CARMEN, to increase its ability to answer questions about the impacts of socio-economic and environmental policies on the European environment.

CARMEN is a simulation model that relates continental environmental and public health problems to socio-economic developments. It is being developed to support policy making and negotiation. Against a background socio-economic scenario, such as 'Business as usual' or 'European renaissance', a regional decision making authority should have a computer model to project the environmental and public health consequences of its own planning on a continental scale.

To be effective the model should be interactive and have a rapid response. Its inputs consist of socio-economic scenarios that are valid for administrative entities, e.g. countries; its outputs consist of time series of environmental and public health indices visualized on geographic maps with relevant grids. To be informative, both policy and impact should be presented together against a background of other policies and normative values or pre-industrial or prevailing circumstances.

The model's time horizon is determined by the uncertainties in the socio-economic developments and is set to twenty years. Many issues are shown in relation to their critical load. The actual loss of societal functions due to these effects may only become manifest beyond the model's time horizon. Loss of functions is thus displayed without time reference under the assumption of continued emissions.

The model is being developed to describe continental issues. The impacts of global environmental problems such as the greenhouse effect will be imported from appropriate models. Care will be taken that the underlying socio-economic developments are consistent. Environmental problems on a strictly local scale will not be dealt with. This implies that issues such as soil pollution near leaching landfills and mining waste are not included. The air pollution in major cities is a local problem, but one of its causes (automobile exhaust) has a broader context. If we could curtail the exhaust of cars by setting up a single European guideline, we would improve the situation in many cities. So the costs of car exhaust reduction can be input to the model and the result would be the degree of relief from exposure.

Status

The current model comprises the acidification and eutrophication pollution issues as depicted in Figure 1.3. The pollution chain is complete from pressure to effects and is based on an external scenario of the GDP of the individual European countries according to the World Bank. The prognostic model that relates economic developments and the penetration of clean technologies to emissions is described is Section 2. Section 3 describes the model implementation of atmospheric transport and transformation processes. Sections 4 and 5 describe the soil and groundwater, and the surface water pollution models, respectively. In the sixth section we present the results of an integrated assessment of the nitrogen load into European rivers and coastal seas. Section 7 gives conclusions and outlook.

In summary, CARMEN is an integrated assessment model for the European environment and related public health issues. The integration is twofold. The assessment covers both the full chain from pressure on the system to its impacts and it contains several interacting continental issues. The project aims to cover the pathways depicted in Figure 1.2. When complete, CARMEN will give greater insight into the efficiency and costs of abatement policies. As an integrated assessment tool, it allows the simultaneous analysis of several environmental issues from sources to effects. It reveals the connection between the pressure and impact in the form of socio-economic developments, local emissions - caused by unsound industrial, agricultural, domestic practices - and pollution problems and ecological and public health consequences.

2. Emissions and the penetration of new technology.

This section describes the module that relates air pollutant emissions to economic, energy, and demographic developments. It consists of an introduction to the model, a sensitivity analysis of the emissions to the penetration of new, clean technologies into the economies, and a presentation of the modelled sulfur dioxide, nitrogen oxide, and particulate matter emission reductions for Europe in the period 1990-2010.

2.1 The emission of air pollutants.

For each individual European country the emission module computes the emissions of sulfur dioxide, nitrogen oxides and particulate matter. The calculations are based on macroeconomic indicators, which represent the activity in the major economic sectors. The user may investigate the sensitivity of the results to the assumptions made regarding the penetration of new clean technology into the economies. The time span of the model ranges from 1990 to 2010.

The module is derived from the EAST model (Bollen et al., 1993; Sauter et al., 1995). EAST was originally developed to estimate the emissions of the countries in transition from centrally planned to free market economies in Central and Eastern Europe and has now been extended to the other European countries. The emission module splits into three algorithms: the partitioning of the total capital stock into stocks of old and new capital equipment, the use of energy carriers, and the emission computation. Figure 2.1 displays a simplified data flow diagram. The hatched boxes represent the external input parameters for the model. Numbered circles indicate the position of the algorithms within the module.

The first algorithm accounts for the capital stock dynamics in economic sectors: industry, conversion, power plants, transport, domestic and agriculture. The capital stocks are partitioned into vintages of old and new capital. Old capital stock is associated with high energy intensities, producing large amounts of waste and pollution. New capital stock, equipped with modern technology, is more energy efficient and relatively clean. Note that the economic indices, Gross Domestic Product, industrial production index, economic lifetime of capital stocks, and demographic development are obtained from external economic models (e.g. World Bank models). To investigate other scenarios, the users may supply their own economic indicator data sets.

The second algorithm evaluates the energy mix needed to satisfy the demand of the economic sectors. The fuel mix matrix relates total energy demand per sector to energy per fuel type. Production with new capital stock needs less energy than production with old capital stock. A specific mix of energy carriers is found for each country.

The third algorithm relates the economic activities and the fuel use to the emissions of the different pollutants. Little information is readily available about the emission factor parameters. These factors have been derived by calibrating the emission module for individual countries to meet independent data sets. The algorithm has not yet been calibrated for all Western countries, due to difficulties in gathering data and to time limitations. For those countries for which insufficient data were available, it has been assumed that growth rates of emissions are equal to emission growth rates of the neighbouring countries.

2.2. Sensitivity analysis.

In recent years emissions from Central and Eastern European countries have dropped in accord with their economic decline. However, the World Bank economic scenario projects an economic recovery after 1995. We may either assume that these countries will invest in western technology or that they will reinstall old equipment. These assumptions have far-ranging consequences for the emission levels. To prove this, we formulated three scenarios, differing in the rate of change to new technology and the fuel shift from coal to gas during the economic recovery period after 1995 (Bollen et al., 1993). These scenarios represent the economic policy choice that must be made in Central and Eastern European countries.

The description of the three scenarios follows.

S1: Base case scenario

In the 'base case' scenario (S1) the share of 'new' capital in Central and Eastern Europe by 2010 is projected to equal 70%, due to investments after the period of economic decline. In Western Europe the share of new capital in 2010 amounts to 65%. The energy efficiency of new power plants, industry, vehicles and heating installations in CEE is assumed to be similar to the WE energy efficiency in 1990. Old equipment is not reinstalled in this scenario. A fuel shift from coal to natural gas is applied in new installations. Western European environmental standards and practices are assumed to be embodied in new capital.

S2: Accelerated substitution

The 'accelerated substitution' scenario (S2) assumes that 95% of all old equipment will be replaced by 2010, meeting the current Western-European standards and practices. As in the base case scenario, a fuel shift from coal to gas is assumed.

S0: worst case scenario

In the 'worst case' scenario (S0) it is assumed that equipment that became redundant during economic decline is reinstalled and reused in CEE countries. The reason for introducing this alternative is that a case study in Russia indicates that the assumptions on the scrapping of redundant capital in the base scenario may be too optimistic. The 'worst case' variant also assumes that new installations for electricity and heat production will use the same fuel mix as the old installations. This assumption reflects a policy aimed at maintaining employment in f.e. coal mines and shows the importance of the fuel switch for environmental quality.

As an example of the model output, the effect of the scenarios on the capital capacity index of the industrial sector in Bulgaria is shown in Fig. 2.2. During the decline until 1994 the industry is based on old capital: 1995 is the first year of the recovery which, according to the World Bank scenario used, will bring total invested capital stock back to its 1990 level in the year 2005. In 1995 the sensitivity analysis calculations generate different results for the first time: the S0 scenario at first reinstalls old capital stock; after 2000 investments in stock equipped with new technology have to be made, as no reinstallable stock remains. However, in 2010 60% of the industry still builds on old capital stock. The S1 scenario does not allow the reinstallation of old capital, and new investments take place as fast as the economy grows and old capital is scrapped. In 2010 new technology has gradually penetrated; still 30% old capital stock is in use. In the S2 scenario old capital is rapidly replaced by new capital stock. In 2010 95% of the capital is already of western technology standard level.

Table 2.1 shows the emission reduction relative to the 1990 levels for SO_2, NO_2, and particulate matter. It appears that the emission reduction is very sensitive for the economic policy. The current reduction plans (1990-2010) for Bulgaria as protocolled during the UN-ECE Convention on Long-Range Transboundary Air Pollution (ECE, 1994) amount to 56% and 77% for SO_2 and NO_2 respectively. The SO_2 value falls well within the range of the sensitivity analysis and affirms the relevance of the reference scenario. The NO_2 protocol value agrees with our estimate in the S0-scenario and appears to be on the safe side. No protocol has been signed for particulate matter emissions.

Table 2.1 Projected air pollution emission reduction factors according to three scenarios regarding the penetration of new, clean technology in Bulgaria (2010 - 1990).

	S0 reinstallment of unused equipment	S1 reference scenario	S2 accelerated substitution
SO_2 emission	79 %	40 %	7 %
NO_2 emission	74 %	54 %	36 %
particulate matter	74 %	40 %	6 %

Figures 2.3, 2.4, and 2.5 demonstrate the sensitivity of SO_2, NO_2 and particulate matter emission, respectively to new technology penetration in Europe. It should be stressed however that calibration of the model is not complete and that results are preliminary. Furthermore, data are not yet available for all countries and interpolation from data for other countries was sometimes necessary.

3. Atmospheric transport.

This chapter discusses the implementation of atmospheric transport (i.e., the process from emission to concentration in the air and/or deposition on the ground). Currently the model contains air transport of the substances SO_x, NO_y and NH_x, which are the major contributors to acid deposition. The emissions of these substances (as SO_2, NO_2, and NH_3) are calculated with a prognostic emission model (see Section 2; Sauter and Bollen, 1995).

The atmospheric transport from emission to concentration and/or deposition is implemented in CARMEN by means of source-receptor matrices, based on the atmospheric transport model TREND (van Jaarsveld, 1995), operating on a latitudinal/longitudinal (LALO) geographical grid. The emissions, resulting from the CARMEN emission module, are calculated per country. These data are attributed to the LALO grid cells, using the spatial distribution of emissions as reported for 1990. The concentrations or depositions are calculated on several different grids. Both operations (i.e., the distribution of the country emissions to LALO grid cells and the transport) are integrated in one source-receptor matrix.

Section 3.1 gives a brief description of the TREND model and the use of its source-receptor matrices for the different geographical grids covering the European continent. In Section 3.2 we show the 1990 emission data and some results that can be obtained with the atmospheric transport model.

3.1 The TREND model applied for Europe.

The model used for the transport calculations is the EUTREND model (van Jaarsveld, 1995) which has been used in previous studies of air pollutant deposition to the North Sea (van Jaarsveld, 1986; Warmenhoven et al., 1989) and the Rhine catchment area (Baart and Diederen, 1991). The model was originally developed for the calculation of transport and deposition of acidifying compounds such as ammonia (Asman and van Jaarsveld, 1990). In these studies, the more general concept was validated by comparing model results with measurements of concentrations in air and precipitation (van Jaarsveld, 1989).

The version used here (EUTREND v1.11 for SO_x, v1.12 for NO_y and NH_x) has recently been upgraded to cover the entire European continent with its marginal seas and to calculate deposition as a function of surface characteristics. The model is driven by meteorological data obtained through The Netherlands Meteorological Institute (KNMI) from the European Centre for Medium range Weather Forecasts (ECMWF) in Reading, England in combination with synoptic surface observations from more than 1500 stations in Europe, also obtained from ECMWF. Atmospheric processes included in the model are: emission, dispersion, advection, chemical conversion and wet and dry deposition. With respect to deposition, it is important to mention here that the model describes the behaviour of pollutants attached to particles as a function of the particle size. Chemical reaction rates are used in the model independently of concentration levels, which means that only linear chemistry can be described. The model has variable spatial resolution, although it is applied here for a fixed receptor grid.

The model has been applied to calculate source receptor matrices on a regular latitude/longitude (1° x 1° LALO) grid. The grid range is (36°,72°) latitudinal and (-12°,60°) longitudinal. 1989 meteorological data has been used. We have aggregated the original LALO emission grid into a country grid. This reduces the dimension of the emission grid from 2592 to 32. This calculation results in a source receptor matrix with dimension 5184 x 32, i.e. the number of LALO cells and countries, respectively.

Given this matrix, it is straightforward to derive source receptor matrices from country to country, region, or EMEP grid square. The different deposition grids are depicted in Figure 3.1. Due to the rapid political and regional changes in recent years the country grid is already out of date. For instance, Yugoslavia is still considered as one country. The necessary updates will be made in the future.

Obviously, the major advantage of this approach is its reduced computer storage space and thus computation time. A drawback is that all economic developments within each country implicitly occur with the same geographical distribution as the ones evaluated here for 1990.

3.2 Results.

In the calculation of the source receptor matrices we distinguish between two source types, depending on their emission within or above the atmospheric mixing layer:

a. source height 20 m, no plume rise,
b. source height 120 m, 40 MW heat capacity.

We therefore split the original emission data into two emission files, one for diffuse sources and point sources with height under 50 m and the second for sources above 50 m. These are called the 'low' and 'high' emissions respectively. Only 'low' emission data are relevant for reduced nitrogen. The emission data sets are depicted in Figure 3.2. A comparison of different emission data sets reveals large inaccuracies for the Russian federation, due to a lack of up-to-date information (Heuberger and van Jaarsveld, 1995).

Figure 3.3 demonstrates the use of the transport matrices for SO_2. The lower panels show the result of the computations for the 1990 and 2010 deposition of SO_2, respectively, by Polish sources only. Westerly winds dominate the transport, as can be seen from the displacement of the deposition to the east of the emission maximum depicted in Figure 3.2. The 2010 deposition is the result of the reference emission scenario discussed in Section 2; deposition rates fall to one third of the 1990 values.

The upper panels show the geographical distribution of the sources which deposit on Poland. Here, we also observe an eastward shift. The most striking feature, though, is that Poland itself is and remains the main contributor to its sulphur acidification problem. In contrast to the results shown in the lower panels, these results cannot be obtained with the original model and must be considered as added value thanks to the mathematical linearisation of the model.

Figure 3.4 depicts total N deposition due to atmospheric transport of anthropogenic emissions over Europe. Intensive animal husbandry, notably in the Netherlands, is responsible for large emissions of reduced nitrogen, which deposits quite close to its source. Nitrogen oxides emitted during industrial processes ('high' sources) and by traffic ('low' sources) cause the widespread nitrogen load.

4. Soils and groundwater.

The abundant input of nitrogen compounds into European soils is mainly caused by human activities: directly by fertilization and manuring of agricultural lands and indirectly by atmospheric deposition. All economic sectors contribute in one way or other to the atmospheric emissions discussed in the previous chapters. Once nitrogen is deposited on the soil, precipitation water will transport it readily. The vegetation takes up most of the load, but eventually the surplus leaches into the ground water or runs off into the surface water. The estimation of plant uptake and water routing thus received a great deal of attention in the model.
Under certain geohydrological circumstances, high fertilizer loads threaten ground water quality. Atmospheric nitrogen deposition loads mainly disturb the composition balance of natural vegetation, which is a subject not yet treated in CARMEN. Both these inputs will lead to nitrogen loads into river basins and coastal seas, which will be discussed in the next chapter, on water.

4.1 Atmospheric deposition, fertilizer and manure application.

The GLOBE report lists agricultural input in Europe (RIVM, 1992; Table 10.3: N application rates (kg/ha/a) to agricultural soil 1990). Agricultural input projections were obtained from the AMEUR-investigation on manure production and from FAO on fertilizer use. These per-country averages (volatilization being already subtracted, and being accounted for in the atmospheric pathway), were allocated to the land use data (van de Velde et al., 1995) in each grid cell. The grid cell load is then estimated by taking the weighed average of the specific land use loads and their areas. It was assumed that all agricultural land (grassland, arable land and permanent cultivation) within a country receives the same amount of nitrogen fertilizer per hectare; manure was distributed over grassland only.

Figure 4.1 shows the resulting agricultural input on a 0.5° x 1.0° grid. According to this preliminary result 10% of the European soils receive more than 200 kg N/ha which is the maximum yearly seasonal crop uptake for arable land. Particularly high loads are found in the Netherlands, caused by intensive animal husbandry and the associated manure surplus. Combining atmospheric deposition (figure 3.4) and agricultural input (figure 4.1), we can construct a map of total input. Agricultural inputs dominate over nearly the whole of Europe, with high (but low in absolute terms) inputs of atmospheric nitrogen in northern Europe and coastal seas.

4.2 Model description.

Fertilizer as well as deposited nitrogen are easily carried away towards the ground water and river system. The water routing algorithm partitions the net precipitation into water that percolates into the ground water and water that runs off towards the surface waters on a grid of 1/6° x 1/6°, covering Europe. In summary, the computation depends on the following parameters (Meinardi et al., 1994):

- aquifer type — highly permeable aquifers having a high ground water fraction,
- texture — coarse textures having a high ground water fraction,
- slope — steep slopes having a low ground water fraction,
- land use — infiltration is highest under forests and zero in urban areas,
- temperature — only in permafrost areas where infiltration diminishes.

The excess of precipitation is estimated using a climate database on monthly precipitation, temperature and cloudiness (Leemans and Cramer, 1991) and the so-called Turc-Langbein formula. This leads to an estimate of the annually averaged precipitation excess on a geographical latitude/longitude grid of 1/2° x 1/2° over Europe. The assumption has been made that the amount of annually averaged precipitation excess on a catchment area is equal to the annually averaged river discharge of a catchment area. We allocated these grid cells to the major river basins and summed the amounts of excess precipitation to compute the annually averaged precipitation excess on the catchment areas. The assumption that these excesses equal the annually averaged river discharges allowed us to validate the water model against observations (Klepper et al., 1995).

The fate of nitrogen in the soil

The soil algorithm that computes the plant uptake and soil denitrification given land use and fertilizer load is derived from the Nload model. Nload was built (van Drecht et al., 1991) and used (van Drecht, 1993) to compute the agricultural nitrate leaching to the ground water in the Netherlands. This approach has been extended with run-off and atmospheric deposition processes (Meinardi et al., 1994). The Nload model needed extrapolation to fit the broader range of European land use and geohydrological characteristics (Klepper and Sauter, 1995).

Figure 4.2 shows the 1990 nitrate concentration in the top soil. This map results from the interaction between nitrogen dose, land use, soil characteristics, and ground water level data. CARMEN computes atmospheric deposition on a 0.5° x 1.0° LALO grid, which is rather coarse for soil and ground water computations. However, the elaboration of all data compares well with the original results obtained with the finer resolution of 1/6° x 1/6° (Meinardi et al., 1994).

Persistent overfertilization threatens the ground water quality. The EC water quality directive sets a maximum allowable concentration for nitrates in drinking water supplies of 50 mg/l (11.3 mg/l NO_3-N) with a guide value of 25 mg/l (5.65 mg/l NO_3-N) or below. In order to satisfy the EC directive, water authorities in some areas may be faced with the need to remove nitrates. To investigate the situation in Europe, we divided the total N load, combining geographical data on atmospheric deposition (Figure 3.4) and agricultural input (Figure 4.1) by the net precipitation to compute the N concentration in the top soil (Figure 4.2). Further elaboration in the water routing algorithm results in a map of the average nitrate concentration in the ground water of the first aquifer.

4.3 Policy implications.

Even given its limitations - since it is highly experimental of nature (Meinardi et al., 1994) - the model supplies policy makers with a regional overview of the nitrate concentration trends in European soils and ground water. The most contaminated ground water is found in the west part of the European continent, where average 0.5° x 1.0° concentrations range to 3 mg/l NO_3-N, which is still well below the EC standard. However, large inhomogeneities within the grid cells do exist. Agriculture with a persistent intensive use of fertilizer on sandy soils, underlaid by permeable and unconsolidated aquifers will exhibit the highest nitrate contamination of the underlying ground water.

In the Netherlands, current proposed policies will barely ameliorate the ground water contamination problem, and it is expected that in the next century 11% of the total drinking water supply abstracted in the Netherlands will need purification before consumption (RIVM, 1991). At an estimated realistic purification cost of *Dfl* 0.50 per m^3, this implies an extra cost of approximately *Dfl* 100 million per annum. At present, there appears to be no viable abatement policy other than the reduction of the intensive animal husbandry sector.

5. Surface Water.

Currently, the CARMEN surface water model contains the nitrogen chain. A model describing the phosphorus chain is ready for implementation. The nitrogen model comprises diffuse agricultural and direct domestic and industrial input, and describes transport and transformation in river systems and effects in terms of annual surface water loads in rivers and coastal seas. Up to now, no uniform European critical loads or even levels for these surface waters have been derived, though a limit value of 2.2 mg/l has been set for the Dutch surface waters [V&W, 1989]. And indeed, the nitrogen inputs in the shallow coastal zones affect fishery yield positively and can be seen as fertilizer. However, increased nitrogen concentrations may also contribute to the recent outbreaks of (toxic) algae in for example the Baltic and Adriatic Sea. These outbreaks have a clear negative impact on fish farming and tourism.

5.1 Diffuse and direct nutrient inputs.

In permafrost and rocky areas water runs off the land surface without having much contact with the subsoil,whereas in permeable, tilled areas the water flows through the top soil layer before it drains into small surface water systems. The type of flow is important for its chemical composition. In CARMEN we have assumed that these soil surface waters have the same composition as the water that percolates into the ground water.

Figure 4.2 shows the 1990 nitrogen concentration in the top soil. The geographical distribution of the load implies that rivers entering the South West part of the North Sea, the Black Sea and the Southern part of the Baltic Sea will carry large loads of nitrogen.

The fate of nitrogen pollution via waste water differs from the previous source in its more direct route to surface water. Since, to our knowledge, there is at yet no concise waste water data set or model for Europe, we estimated sewage production from population density. For simplicity we assumed a single multiplication factor to calculate nitrogen load from population numbers. This implies that:

- the fraction of nitrogen removed in sewage treatment plants and the fraction of the population served by waste water treatment plants is treated as a constant; and
- the ratio of industrial waste water production to population is treated as a constant.

Notably, both the constant-treatment-fraction and the constant-industry-fraction can give large errors. Fortunately, both fractions tend to cancel: countries with a predominantly rural population generally have relatively low access to treatment plants, but the same countries may be expected to have a relatively low industrial waste water contribution.

5.2 Model description.

We can calculate total discharge of nitrogen by combining land-based (atmospheric and agricultural) and population-based (waste water) inputs per catchment area. The model now requires the estimation of a few parameters (assumed to be constants for the whole of Europe) of which the loss rate due to denitrification and the proportionality of inhabitants to sewage inputs rank as the most important. These parameters are determined by calibration on available nitrate concentration data, which were sampled at the river mouths of the larger catchment areas in Europe (Klepper and Sauter, 1995).

Calibration was performed for total discharge rather than concentration, i.e., the larger river basins received extra weight according to discharge. The first calibration parameter can be interpreted as the population-related nitrate load. Calibration results in 14.6 g/inhabitant/day for this parameter, which agrees well with observed values (CBS, 1987). The value of the second parameter (dimensionless) gives the final nitrate yield as a function of total nitrogen input. Independent estimates give a loss due to denitrification of 70-80%; combining this with a NO_3:N_{total} ratio of approximately 0.7 we would expect a value of 0.14-0.21. Our calibration leads to the slightly lower value of 0.12. This might be explained by additional nitrogen losses in the river, but appears to be within the uncertainty margin of the estimates.

If we compare the two nitrogen inputs in their contribution to water quality, we see that nitrogen from waste water is the dominant factor. The total population in Europe is 660 10^6, giving 2.8 10^6 tonnes N/a. For agriculture and atmospheric inputs to the entire area (i.e., not only on agricultural land), an average value is some 40 kg/ha/a or 4 tonnes/km^2/a. Combining this estimate with the total area of 9.85 10^6 km^2 and a 95% loss due to plant uptake and denitrification, we estimate that some 2.0 10^6 tonne N enters the sea annually.

During winter months, nitrate concentrations in the North Sea can be accurately predicted by analyzing its fresh water fraction (calculated from salinity), i.e., clean ocean water simply dilutes polluted river water. During the summer this simple relation no longer holds, as nitrate is transformed to various other forms of nitrogen, or temporarily stored in water below the thermocline, in bottom sediments, etc.. As a first approximation, however, there appears to be a linear relation between nutrient inputs and effects which makes the calculation of nitrate concentrations *as if* these would behave conservatively a very good proxy for ecosystem effects.

We, therefore, derived a simple empirical advection-diffusion model for the coastal seas of Europe (Klepper et al., 1995). In total 41 compartments describe five adjoining coastal sea areas: North and West Europe (Gulf of Biscay, Irish waters, North Sea, Baltic Sea, and Norwegian coastal Sea), East Europe (Black Sea and the Sea of Azov), South Europe (Balearic Sea, Ligurian Sea, and Tyrrhenian Sea), Adriatic Sea and Aegean Sea. The model was calibrated using observations of caesium-137, salinity and fresh water discharge.

Nitrate input to the seas is computed by summing nitrogen loads - concentration (Figure 5.1) times discharge - at the river mouths and direct atmospheric deposition to coastal seas (Figure 3.4 has been translated into Figure 5.2). Replacing the above fresh water input with this nitrate input, and replacing salinity boundary conditions with a constant nitrate concentration of 0.1 mg N/l allows us to calculate potential nitrate concentrations. The term 'potential' indicates that all biological transformations and loss rates in the coastal seas are disregarded.

5.3 Results.

The 1990 fresh surface water quality map (Figure 5.1) shows two major problem areas in Europe. In the North-Western part of Europe low quality is mainly related to high inputs (intensive agriculture, high population density). In some areas of the Mediterranean low quality is not so much due to high inputs (per unit area they are lower than in Western Europe), but to low discharges. These cause a small dilution of the pollutant load.

The 1990 sea water quality map (Figure 5.3) shows two major problem areas: the Baltic Sea and the Black Sea - Sea of Azov. In comparison with the North Sea, absolute loads are not excessive, but coincidence with low exchange between these brackish seas and unpolluted oceanic or Mediterranean waters.

The nitrogen model will be improved by a better estimate of agricultural inputs, in particular the subdivision of some pre-1990 Eastern European countries into their present political units (Soviet Union, Czechoslovakia, Yugoslavia). Also, catchment area borders need to be more accurately delineated. Regarding the high contribution of waste water, it seems worthwhile to make the distinction between domestic and industrial waste and between treated and untreated sewage more explicit. This task will be undertaken by a number of European institutes, including RIVM, in the GREAT_ER project, that will start in 1996.

The presently calculated river-basin averages may not be sufficient to indicate the risk of pollution. Particular river stretches may - for certain time periods - exhibit much higher concentration values. For coastal seas, a catchment-areal average is obviously sufficient, and time-scales are probably sufficiently long to ignore seasonal differences in loads. In the North Sea, in particular, large temporal and spatial variations have been observed, which cannot be forecast with the model. To analyse the effects of policy alternatives we may obtain concentration projections by superimposing these anomalies on the trends of the averaged values that we have shown.

6. Integrated assessment applied to the nitrogen load in the European rivers.

In this chapter we present an example of an integrated assessment, supported by the application of the 1995 version of the CARMEN model. The total nitrogen load into affected coastal seas is analysed in terms of contributing economic sectors. CARMEN enables the efficacy of sectoral emission reduction measures to be quantified in an integrated context. The analysis is based on computations according to Figure 1.3: all previously described modules of CARMEN are involved. The chapter comprises a summary of those parts of the model that consider nitrogen compounds, and a presentation of the results for three illustrative areas: the Baltic Sea, the North Sea, and the Black Sea. It will be shown that this integrated assessment enables us to concentrate the environmental policy process on those economic sectors that contribute most to the eutrophication problem.

6.1 The nitrogen load in European rivers.

Due to direct and diffuse inputs to the river catchment areas, many European rivers carry a large load of nutrients. In this example we focus on nitrogen. High nitrogen concentrations increase the risk of occasional oxygen shortages with consequent adverse effects, such as (commercial) fish death and poisonous algae blooms. It is well understood, but hard to analyse in quantitative terms, that all economic sectors contribute to this problem. Using the CARMEN model as an analysis tool, we may discern these contributions in each river basin and consequently the coastal seas downstream.

Figure 6.1 details the data flow of the model. The top line depicts the economic sectors involved. *Consumers* and *industry* emit nitrate directly into the rivers via the sewage system. By applying more fertilizer and manure than the vegetation uptake, *agriculture* may optimize its financial returns, but will overload the soil. The surplus will either evaporate as reduced nitrogen or leach into the ground water or run off the soil directly into the surface water system. Airborne reduced nitrogen does not travel far, and it will deposit again on the soil or on nearby coastal seas. Nitrogen oxides emitted to air by *power plants*, *traffic*, and *industry* do travel further away. However, it will also eventually deposit on the soil or sea.

The emissions of nitrogen to the air are closely connected to the issues of acidification and oxidation by ozone, as depicted in Figure 1.2. Policy measures aimed at reducing these emissions are directed to these issues, but they may also contribute to the amelioration of the eutrophication issue. CARMEN can readily show this potential by making an analysis per economic sector. We also computed the relative contribution of air pollution to the nitrogen load into the seas. We then found that only in the Black Sea and the Ionic Sea the river system load completely dominates air pollution. Atmospheric deposition makes a large relative contribution in the remote Scottish coastal waters. However, absolute nitrogen amounts are small, as can be seen in Figure 5.2.

Sensitivity analysis.

To demonstrate the sensitivity of nitrogen concentration levels in coastal seas to emission reductions, we varied the contributions of each of the economic sectors and scaled the effects to the load. If the model had been linear, these sensitivities would have been the same as the effective contributions by the economic sectors. However, in a nonlinear model - like CARMEN - this does not hold and the sensitivities must be regarded as the relative effects of a 10% change in each of the economic sectors.

We selected three areas for this demonstration: the northern part of the Baltic Sea, the North Sea, and the Sea of Azov. The northern part of the Baltic Sea is situated well away from intensive industrial and agricultural areas. There is little exchange with other water, however, so local inputs may accumulate. In contrast, some of Europe's most intensively populated river basins discharge into the North Sea. There is much ventilation with relatively nutrient-poor water from the Atlantic Ocean through the English Channel, which tends to keep the spatial average eutrophication level low. However, some eutrophication problems do occur in coastal zones characterized by large fractions of river water. The Sea of Azov is a notorious example of significant eutrophication by large agricultural and sewage water loads, which are carried by the river Don. This shallow sea has little exchange with the Black Sea, which itself is already threatened by eutrophication from the river Danube.

The computations follow the reference scenario, which was mentioned in section two, to show the effects of the current policies. At present, CARMEN does not contain a scenario for the improvement of the European sewage system. The current model contains simple, per-inhabitant nitrogen emission loads. Further development of the model may improve this. The GREAT-ER project (Section 5) will enable us to use regional data. The EU directive on urban waste water treatment, encouraging the construction of waste water plants for all agglomerations of more than 10 000 population equivalents (p.e.) ultimately in the year 2000, will provide us with a scenario.

The reference scenario includes a scenario for the nitrogen emission of the agricultural sector (Hoogervorst and van Egmond, 1994). Apart from the Netherlands and Bulgaria, it is not expected that the nitrogen load will diminish. In the Southern, Central and Eastern European Countries the load will grow due to an expected increase in intensive animal husbandry. This also becomes obvious from the reduced nitrogen protocol of the Convention on Long-Range Transboundary Air Pollutants. There are hardly any countries with reduction plans other than the stabilisation of the emissions at the 1990 level.

6.2 Results.

Figure 6.2 shows that in the Northern Baltic Sea we may expect that the policies to reduce air pollution will work. In 1990 the nitrogen load was most sensitive to NO_x emission reduction, notably from traffic exhaust. It appears that by 2010, policy makers should direct their attention to the reduction of the load from agriculture and the sewage systems, and there will be little to gain from further NO_x reduction programmes. NO_x emission reduction does not play a major role for the quality of the North Sea and the Sea of Azov. Agriculture input, both through the air and via runoff, will become even more dominant due to the expected intensification in the agricultural sector of the Russian Federation (Figure 6.3).

The sensitivity analysis for the North Sea indicates that policy makers should investigate both the emission reduction of the agricultural sector and sewage treatment plants (Figure 6.4). Regional differences may be important. For the Dutch stretch of the river Rhine, for example, agricultural load is about twice that of the sewage treatment plants, while these two loads balance for the North Sea as a whole.

We have shown that CARMEN can provide a screening method to analyse the fate of nitrogen emissions into the environment. We have reported a sector sensitivity analysis, but using CARMEN one may also analyse the contribution of particular watersheds or countries. The policies to reduce the nitrogen oxide load have a positive spinoff to the quality of coastal waters. This tentative analysis indicates a recommendation to pay most attention to the development of abatement strategies directed to the sewage treatment plants and agriculture. Confirmation of this implication for policy making may need additional support from a fine-tuned version of the current model, possibly including the incorporation of subregional and seasonal variability into the modelling concept.

7. Conclusions and outlook.

The elements of the current version of CARMEN are depicted in Figure 1.3. Four sections illustrate the main submodels, which all have been fully documented in separate reports. Section 6 demonstrates the versatility of the computer program. In support of policy-oriented applications, we analyzed the sensitivity of the nitrogen load of three European coastal seas by varying the emissions of the economic sectors involved. A similar analysis could also be carried out by varying the contribution per watershed or country, yielding geographically explicit sensitivities. This approach may help to find the most efficient targets in the policy process.

More elements.

Currently, CARMEN contains only submodels and datasets constructed at RIVM. In the near future, other RIVM work will be integrated into the model, on the issues of urban air pollution, and of intoxication by heavy metals and persistent organic pollutants for example. IIASA and EMEP may contribute to CARMEN with source receptor matrices for a submodel that describes the damage by photochemically produced ozone. The international GREAT-ER project will strengthen CARMEN's regional power regarding issues in the surface water compartment by providing detailed information on local emissions, and hydrology.

The resolution of the model is coarse: 0.5° x 1° spatially and one year temporally. This may be too coarse for some assessments. The incorporation of subregional and seasonal variability will enhance the possibilities of the model. If the models are sufficiently linear, or can be made so around their current inputs, we may achieve this by overlaying anomalies and statistical extremes upon the annual trends. This would maintain CARMEN's speed and versatility and enable risk analysis to be performed.

CARMEN aims at supporting negotiations for new protocols. It will be better suited to this task if the actors in the negotiating process are familiar with and have faith in the - correct - working of the model. Therefore, RIVM should promote international collaboration on the extension and validation of the model. Also, as a kind of reliability analysis, we would welcome the idea of coexistence of RIVM and foreign submodels.

We may now use CARMEN for efficacy studies of policy measures. To investigate the cost-effectiveness of measures we need to introduce cost curves into model. This concerns all economic aspects of abatement strategies including the costs of measures and the social costs of the damage, that will occur if no precautions are taken. The construction of a damage-cost inventory is the main task for a specialized Task Force of the UN ECE. RIVM should support this work to enhance the applicability of its research for the identification of *win-win* situations for both economy and environment.

Optimization.

A complete overview of the marginal costs of abatement policies would enable the use of CARMEN as an optimization tool. Instead of the forward calculations, which evaluate the effects of given policies, we would carry out backward calculations to evaluate which measures should be taken and to what extent, given the critical values of the effects. The watershed approach followed in CARMEN enables one to distinguish between regions depending on their economy, hydrology and climate. This is in line with the EU principle of subsidiarity, which, where possible, passes control to regional authorities.

However, some abatement policies have large social impacts, which make the policy process less fit for computerized optimization only. Nevertheless, optimization is a powerful tool to support the process of defining optimum strategies to combat the pressure on Europe's environment as has been proved by the use of the RAINS model by the Convention on Long-Range Transboundary Air Pollutants. Here too, it is important that these assessments are based upon models and data sets that are open to inspection and constituted in international collaboration.

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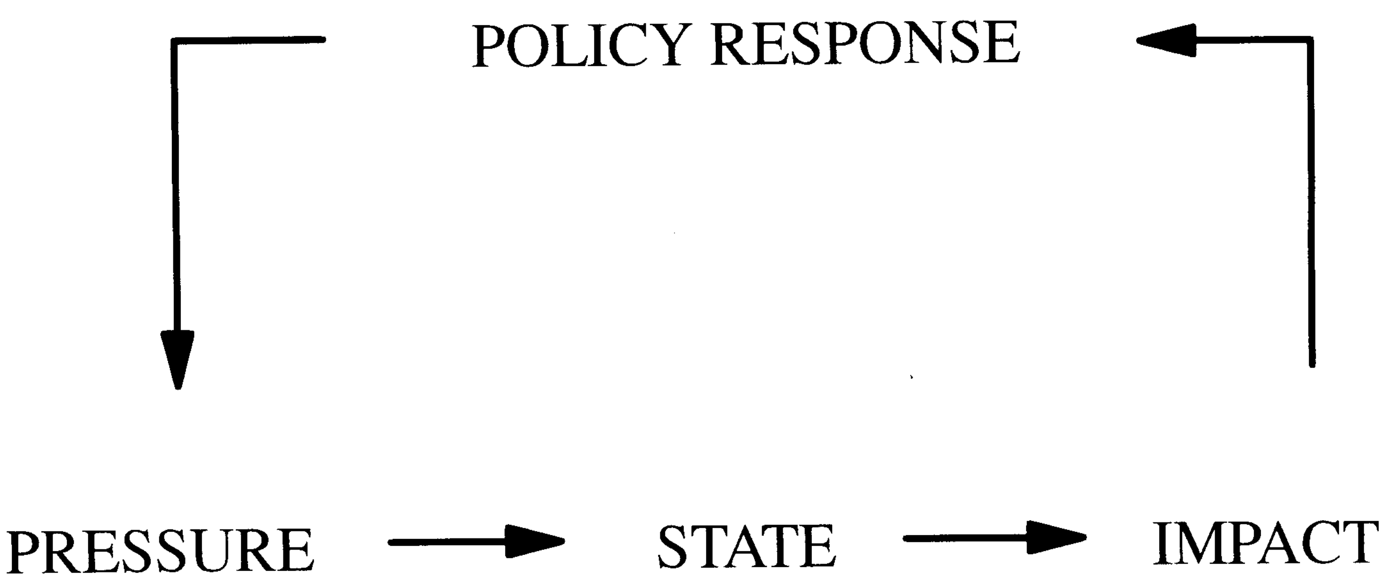
9. Figures.

Figure 1.1 Cause-Effect Relationship between Pressure, State, Impact, and Policy Response .



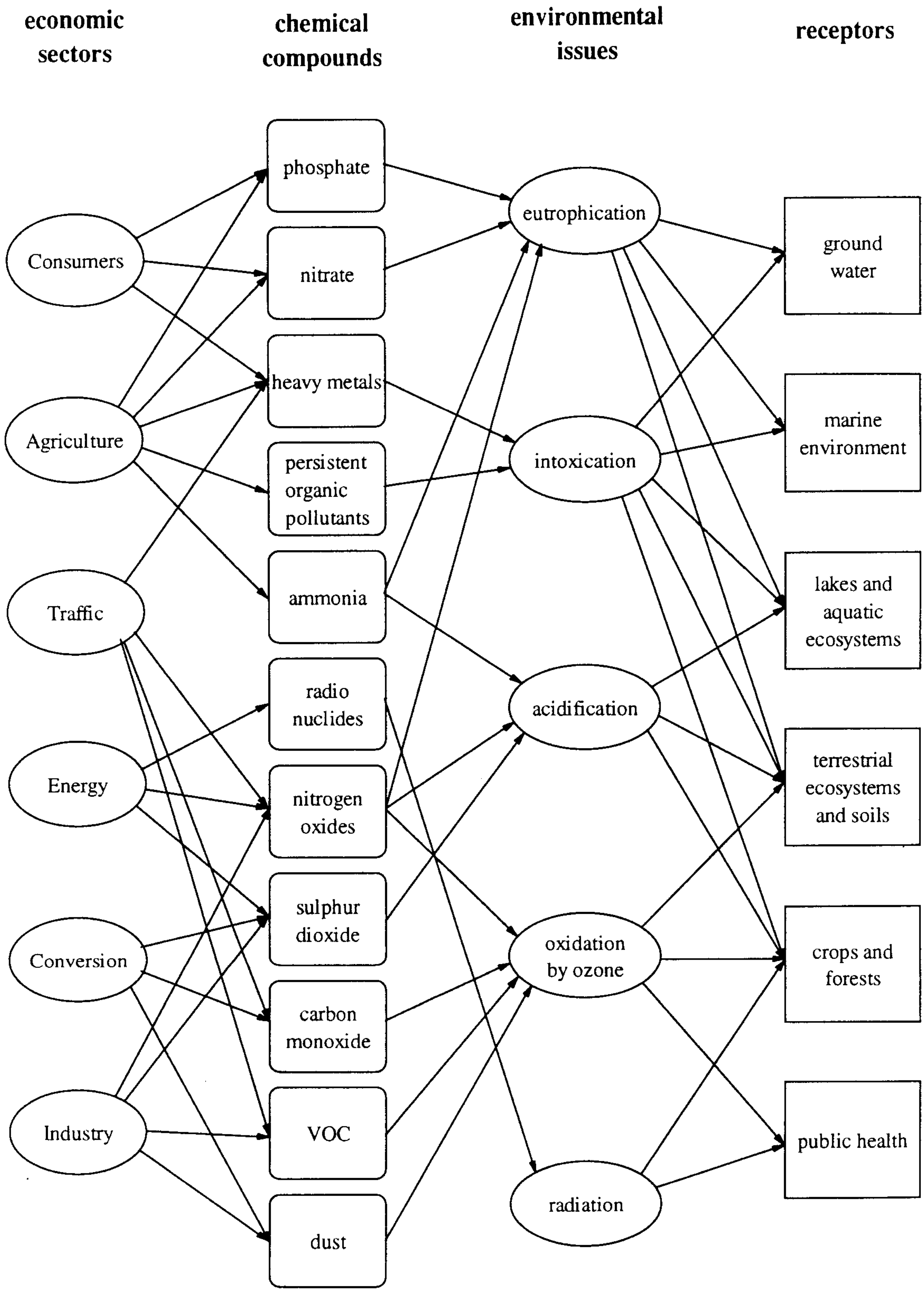


Fig 1.2 The connection between several economic sectors, pollutants, environmental issues, and receptors adapted from Grennfelt et al. (1993).

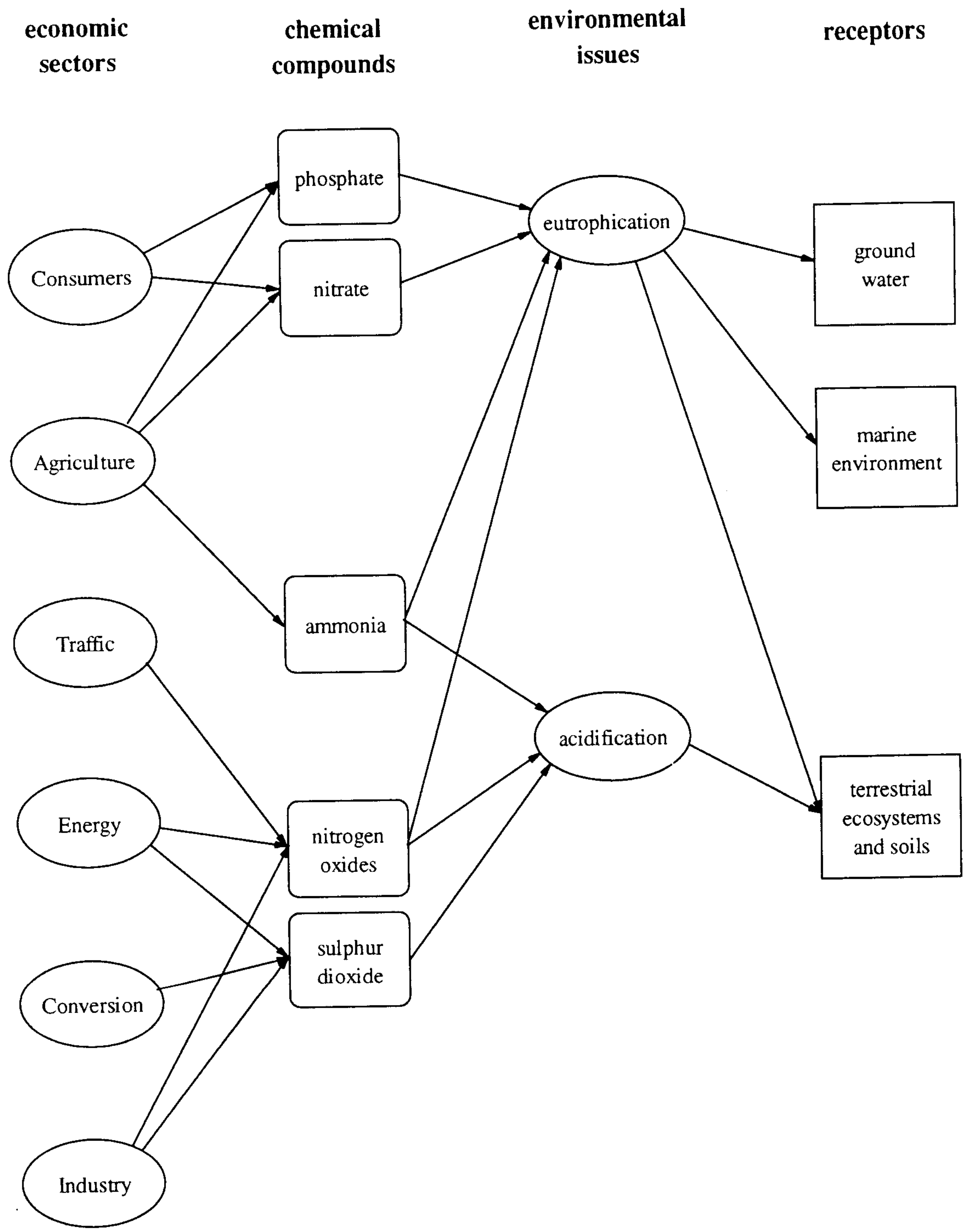


Fig 1.3 Schematic overview of the current version of CARMEN.

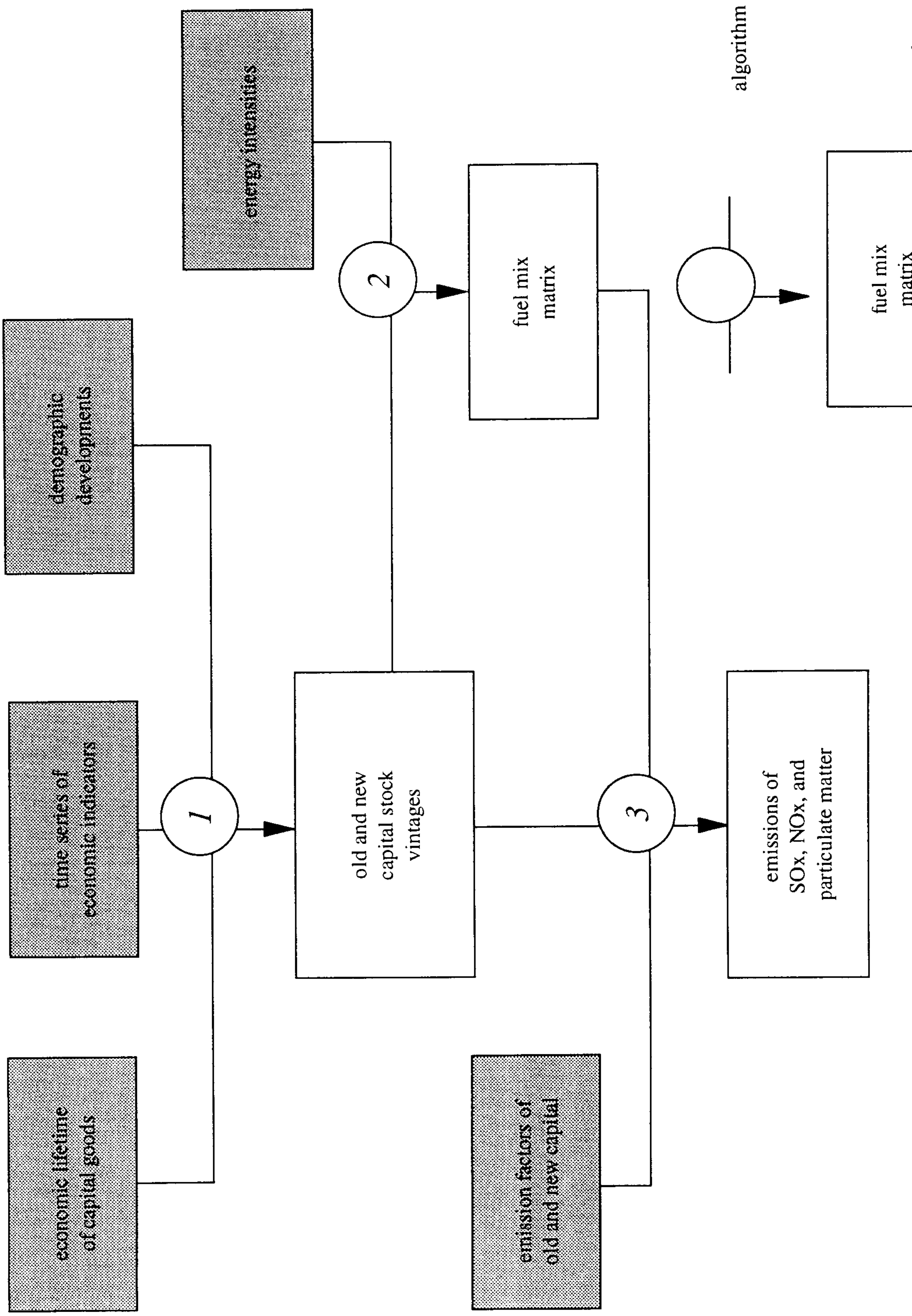
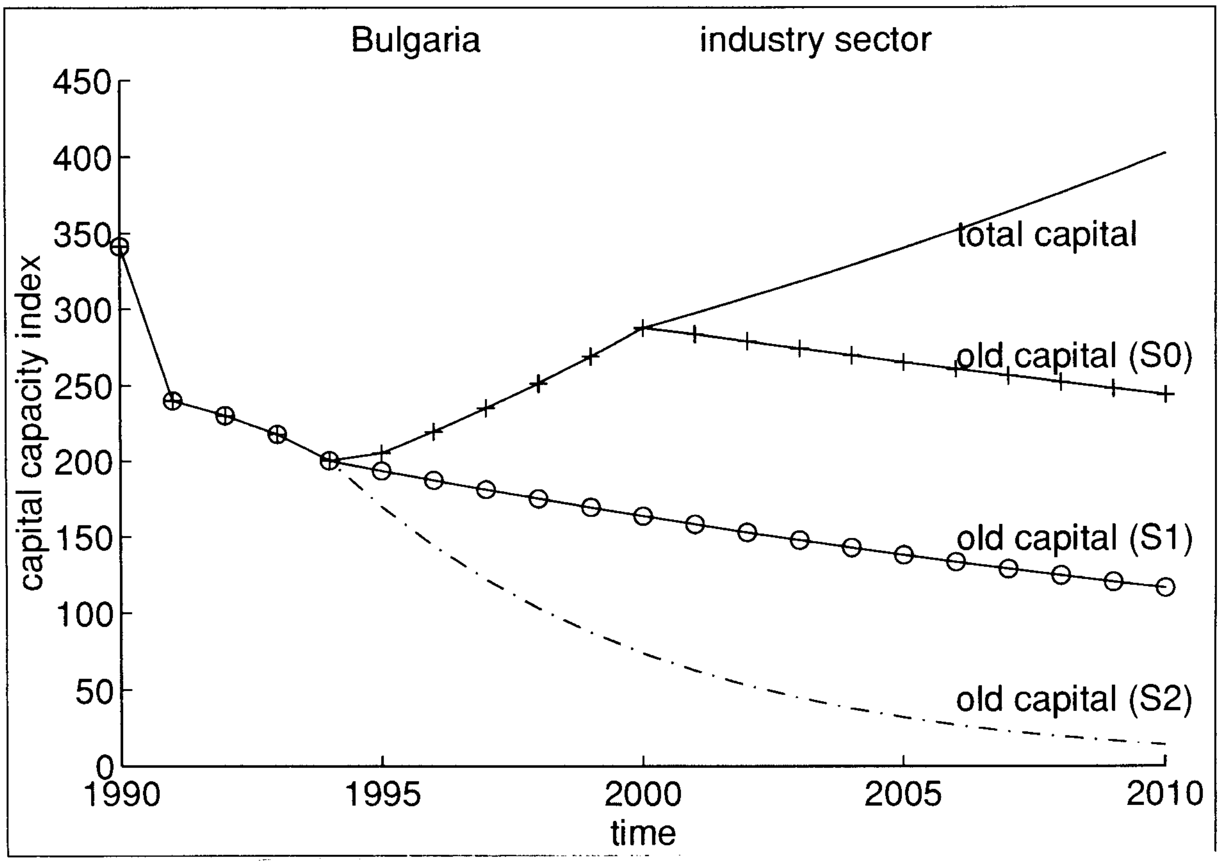


Fig. 2.1 Data flow diagram of the CARMEN emission module.

Figure 2.2 Capital capacity index of the Bulgarian industry sector for different scenarios of clean technology penetration.



The top line denotes total invested capital in the Bulgarian industry sector according to the economic scenario developed by the World Bank. Starting from 1994, there are three policy options to invest in new technology. See text for the assumptions in scenarios S0 (worst case), S1 (reference), and S2 (accelereated substitution). The remaining - and polluting - investment shares in 'old' capital, denoted by + + + , o o o , and – · – · – ·, respectively, indicate the wide range of environmental impact the policy options have.

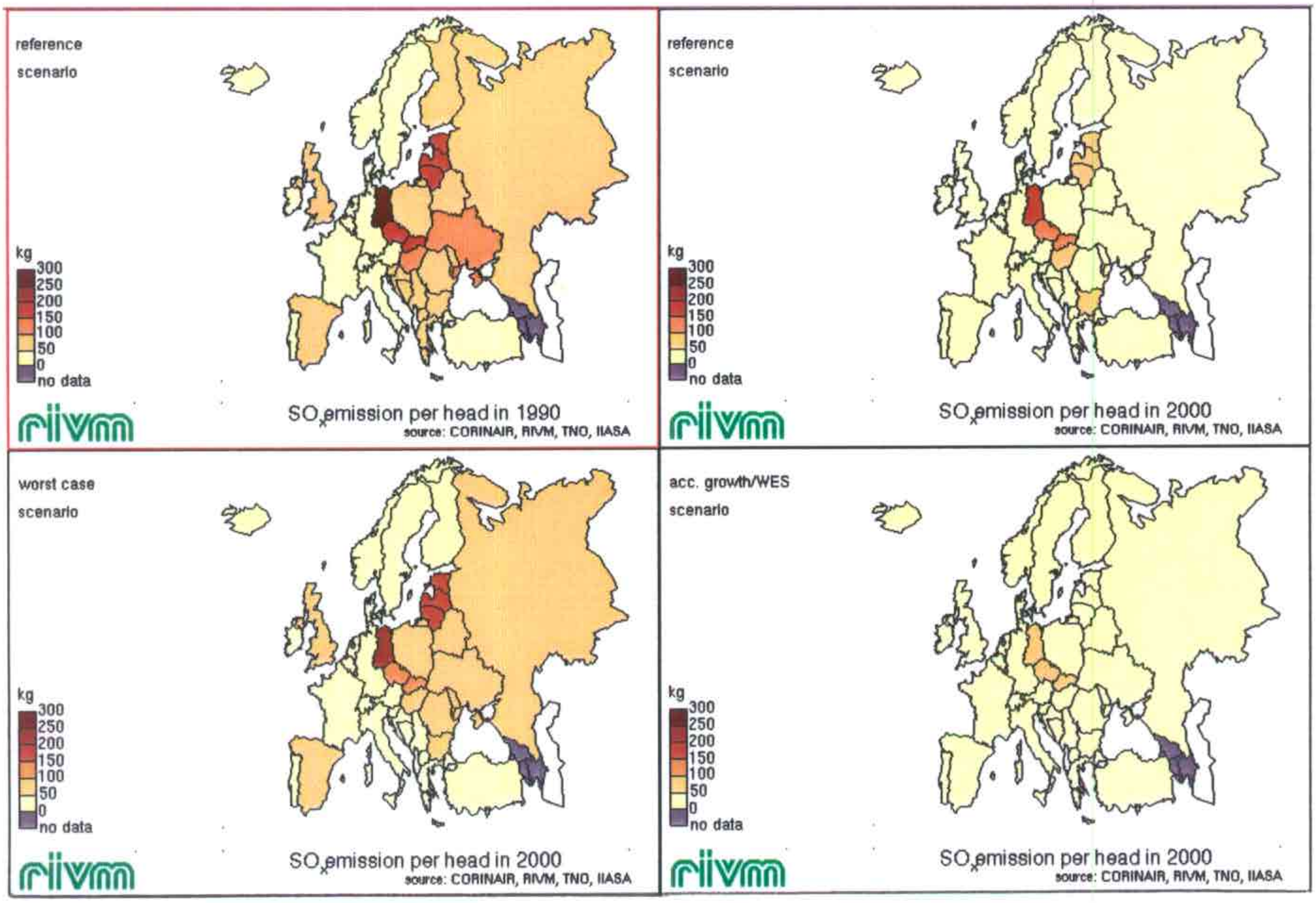


Figure 2.3 SO_x emission projection for the year 2000 using the reference, worst case and best case technology penetration scenarios.

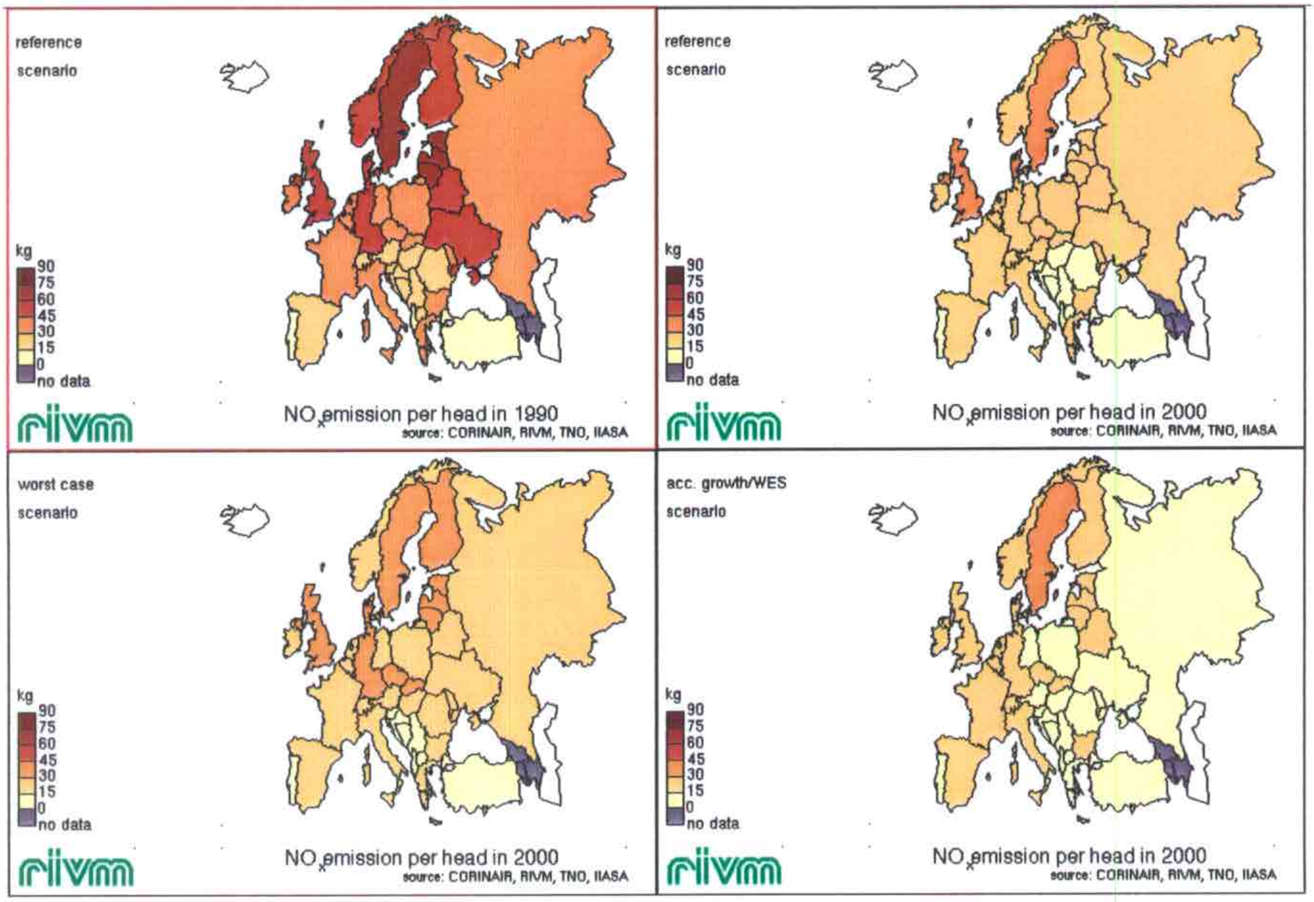


Figure 2.4 NO_x emission projection for the year 2000 using the reference, worst case and best case technology penetration scenarios.

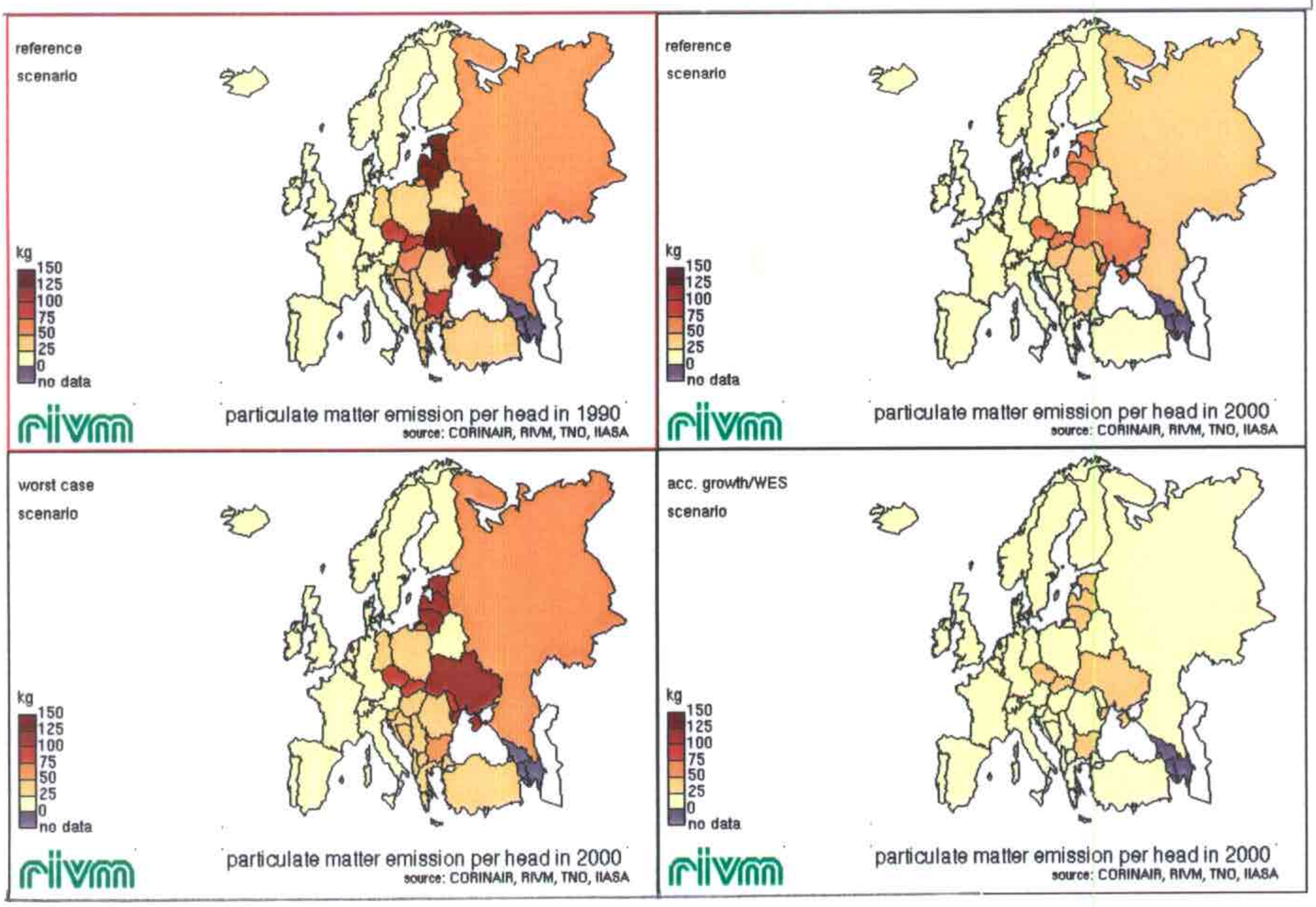


Figure 2.5 Particulate matter emission projection for the year 2000 using the reference, worst case and best case technology penetration scenarios.

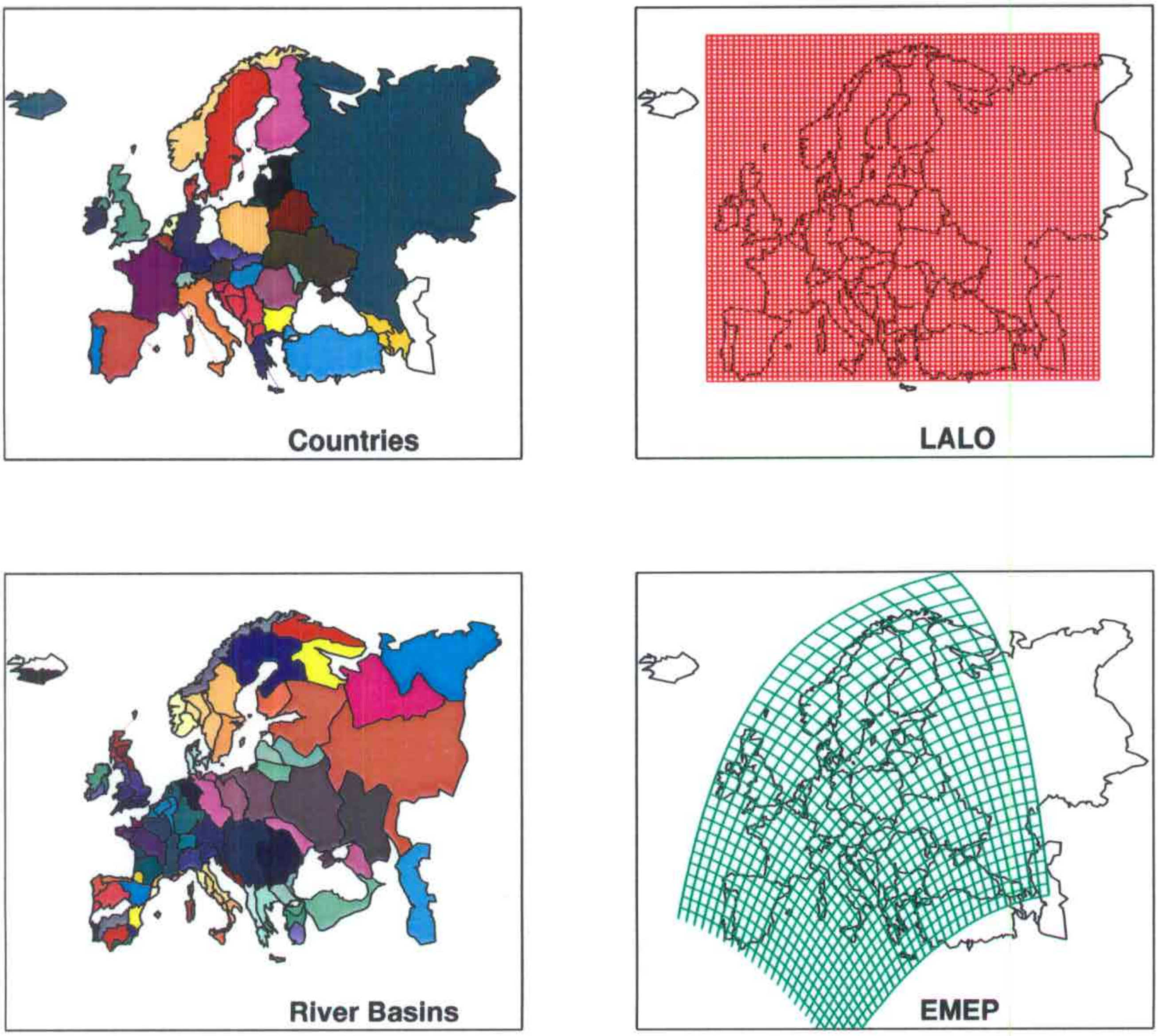


Figure 3.1 Geographical grids used for CARMEN.

Within the model we switch to different grids.
Socio-economic entities apply to the - 32 - country grid, geophysical computations are performed on a regular latitude/longitude (½° x 1° LALO) grid. The grid range is (36°,72°) latitudinal and (-12°,60°) longitudinal. Some of the results can also be depicted on the skew EMEP grid.
The 'wet' computations are performed on a grid spanned by 101 contiguous river basins and 41 coastal seas.

Figure 3.2 1990 Emission distributions.

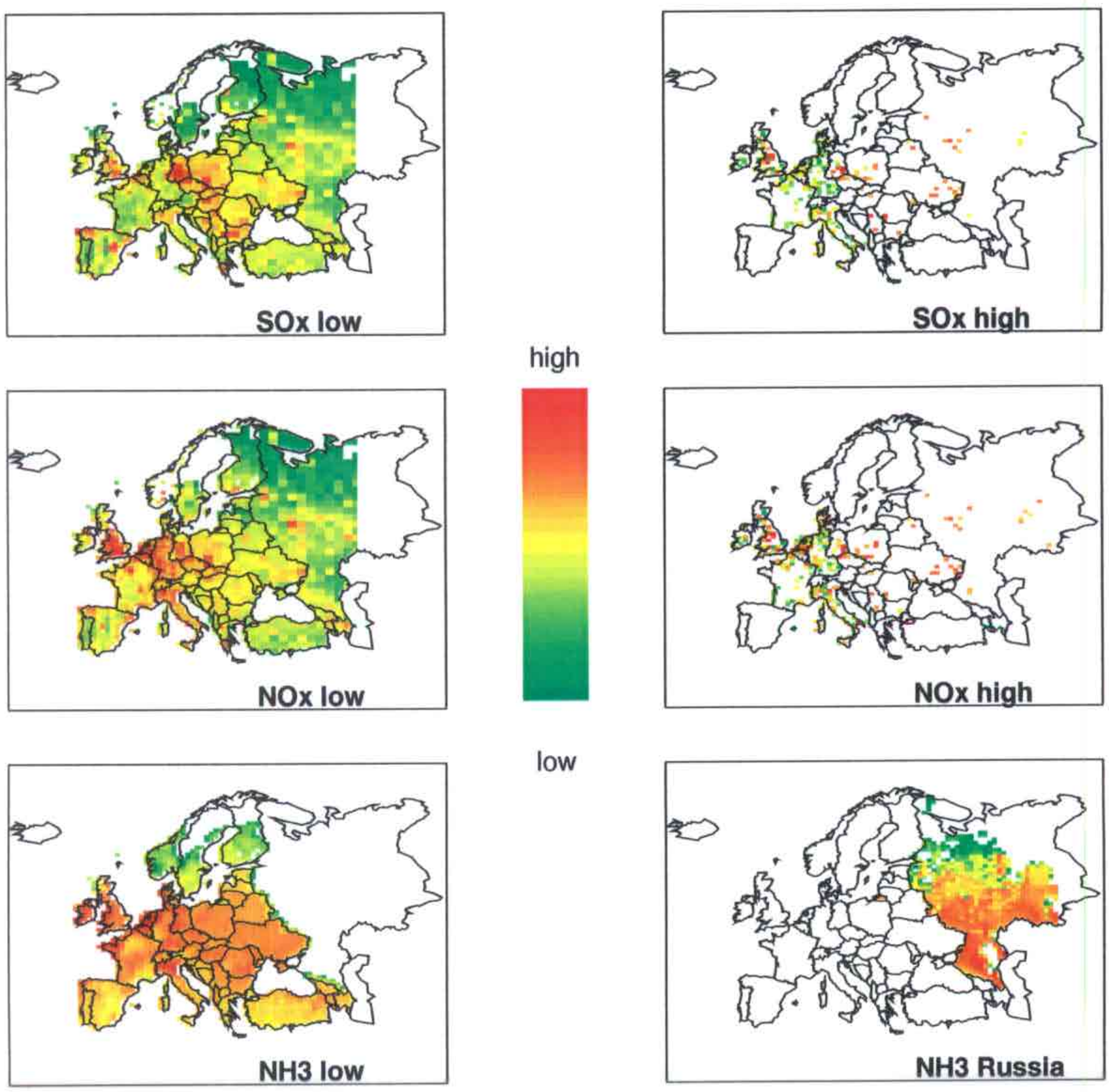


Figure 3.3 The 1990-2010 trends in SO_x import and export for Poland only. Using the reference scenario for new technology penetration, Carmen projects a factor nine emission reduction.

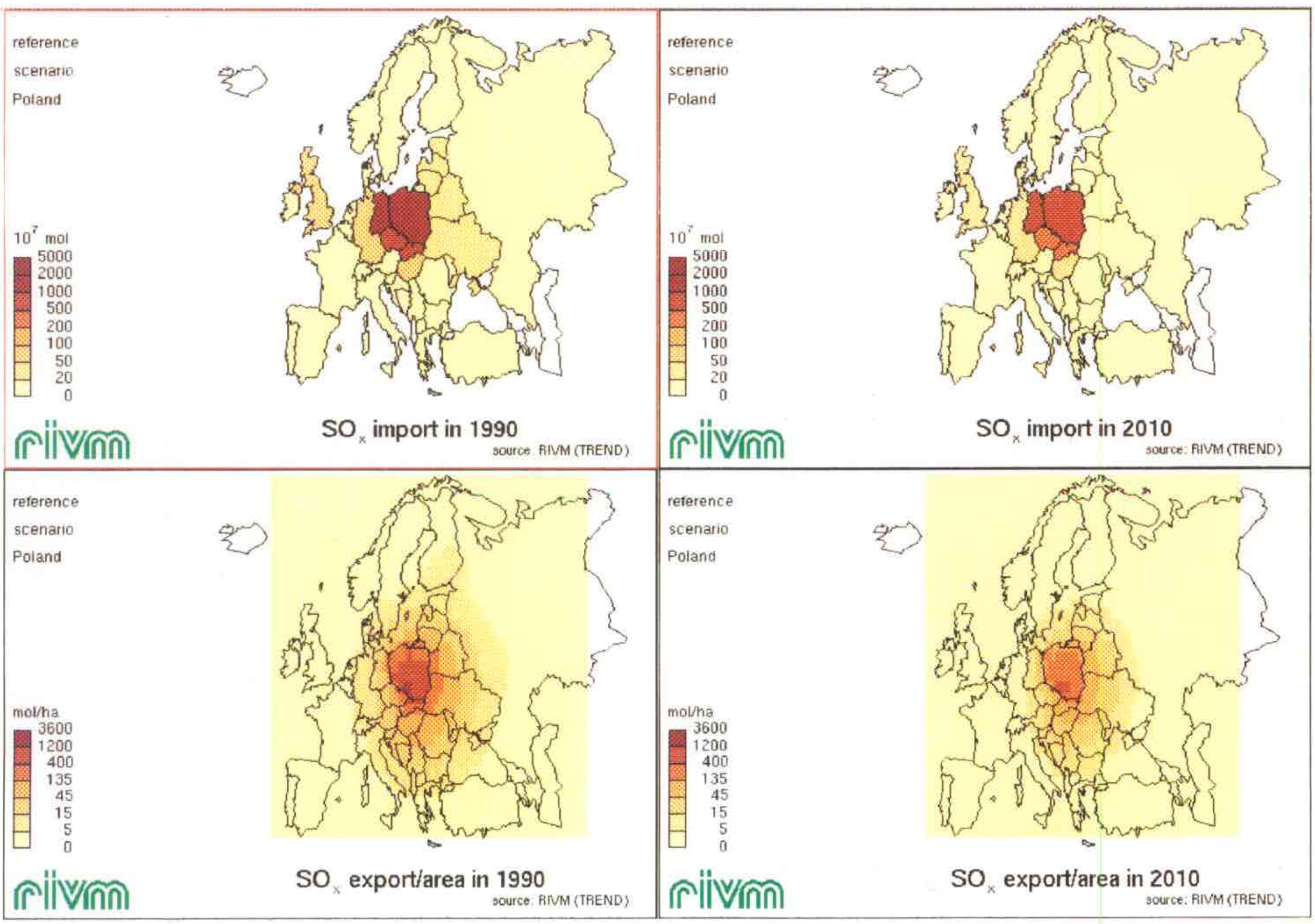


Figure 3.4 1990 Atmospheric deposition of nitrogen.
In the left hand panel, the legend also displays the relative size of the land area with the specific loads.

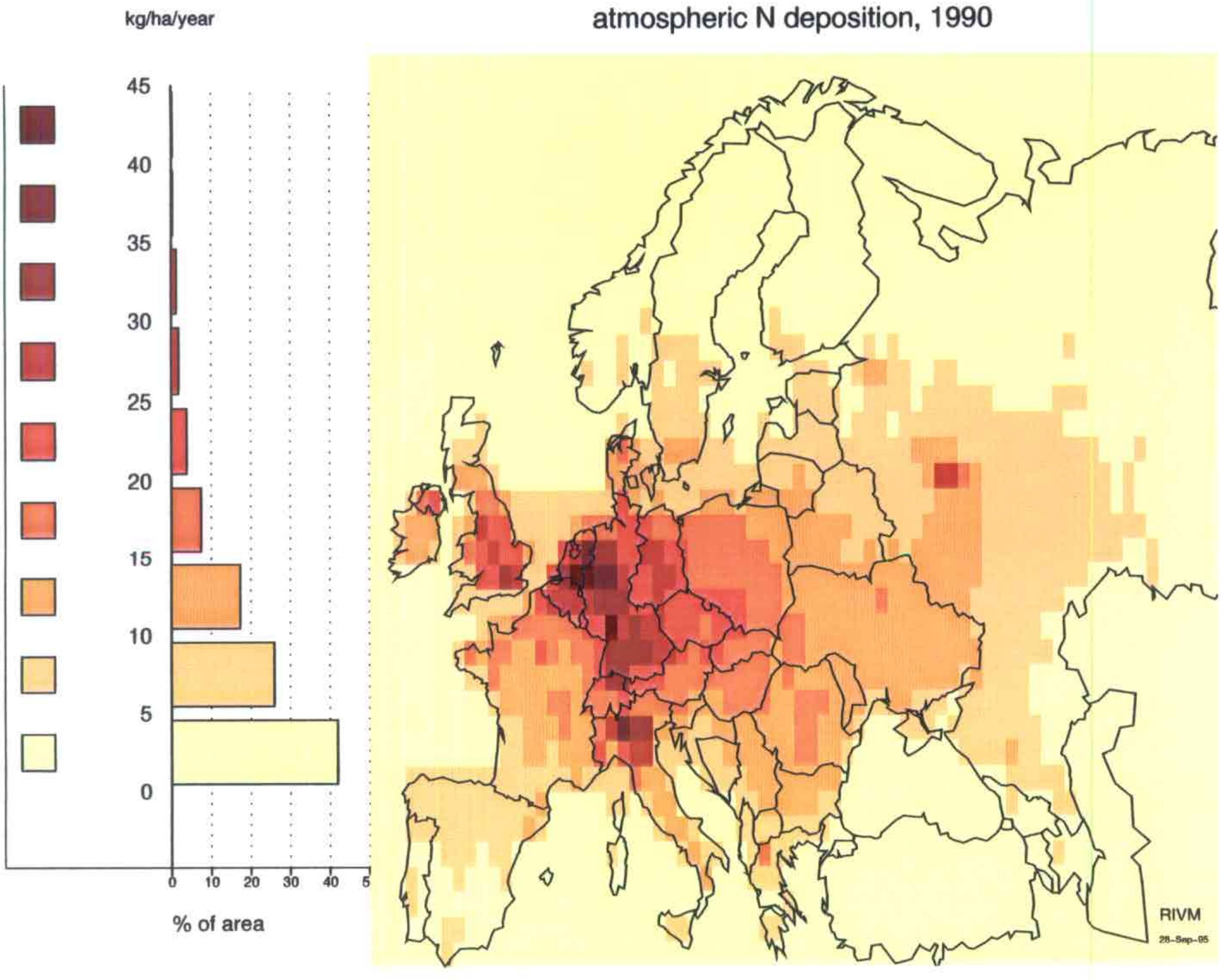


Figure 4.1 1990 Agricultural nitrogen load.

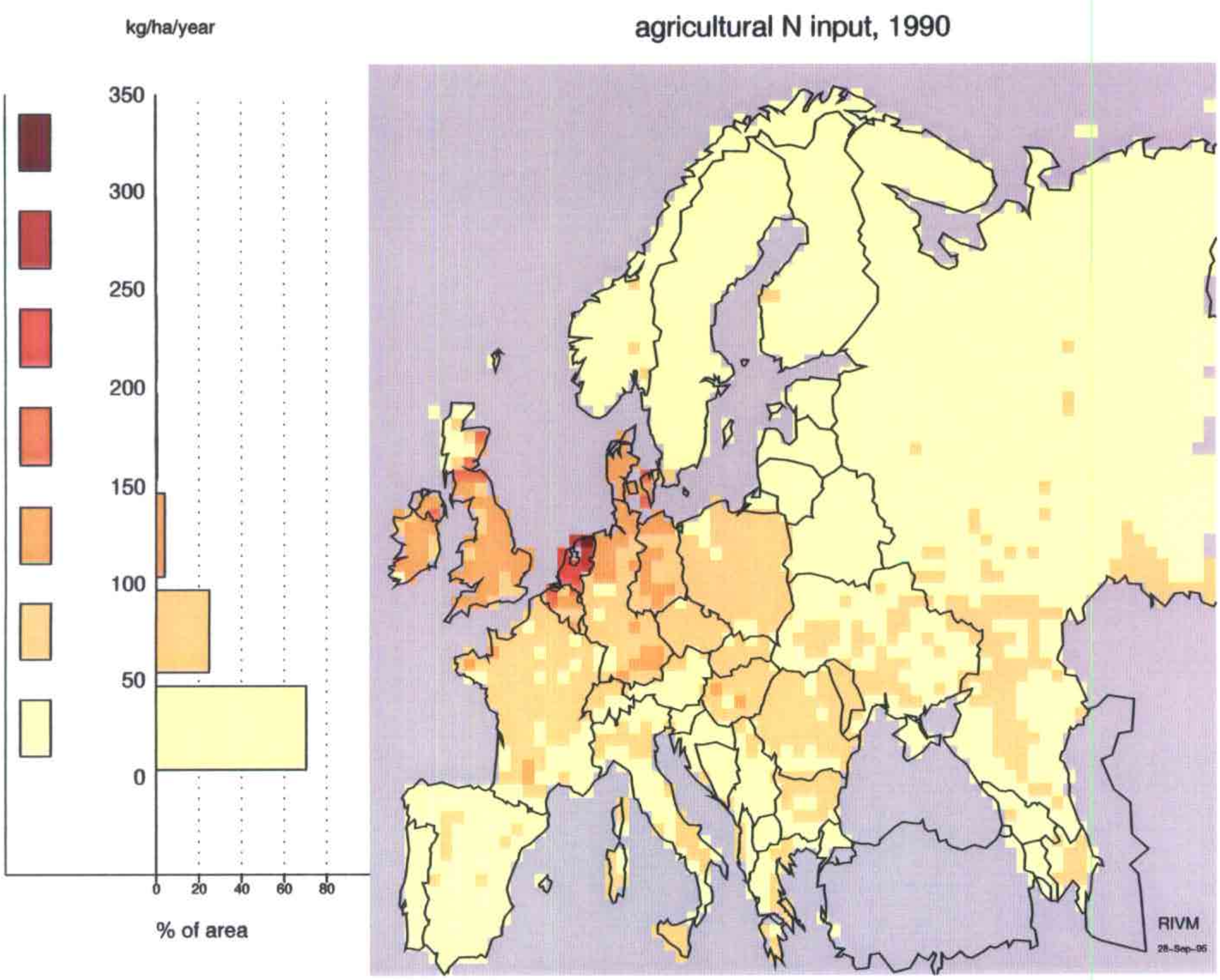


Figure 4.2 Nitrate concentration in the top soil.

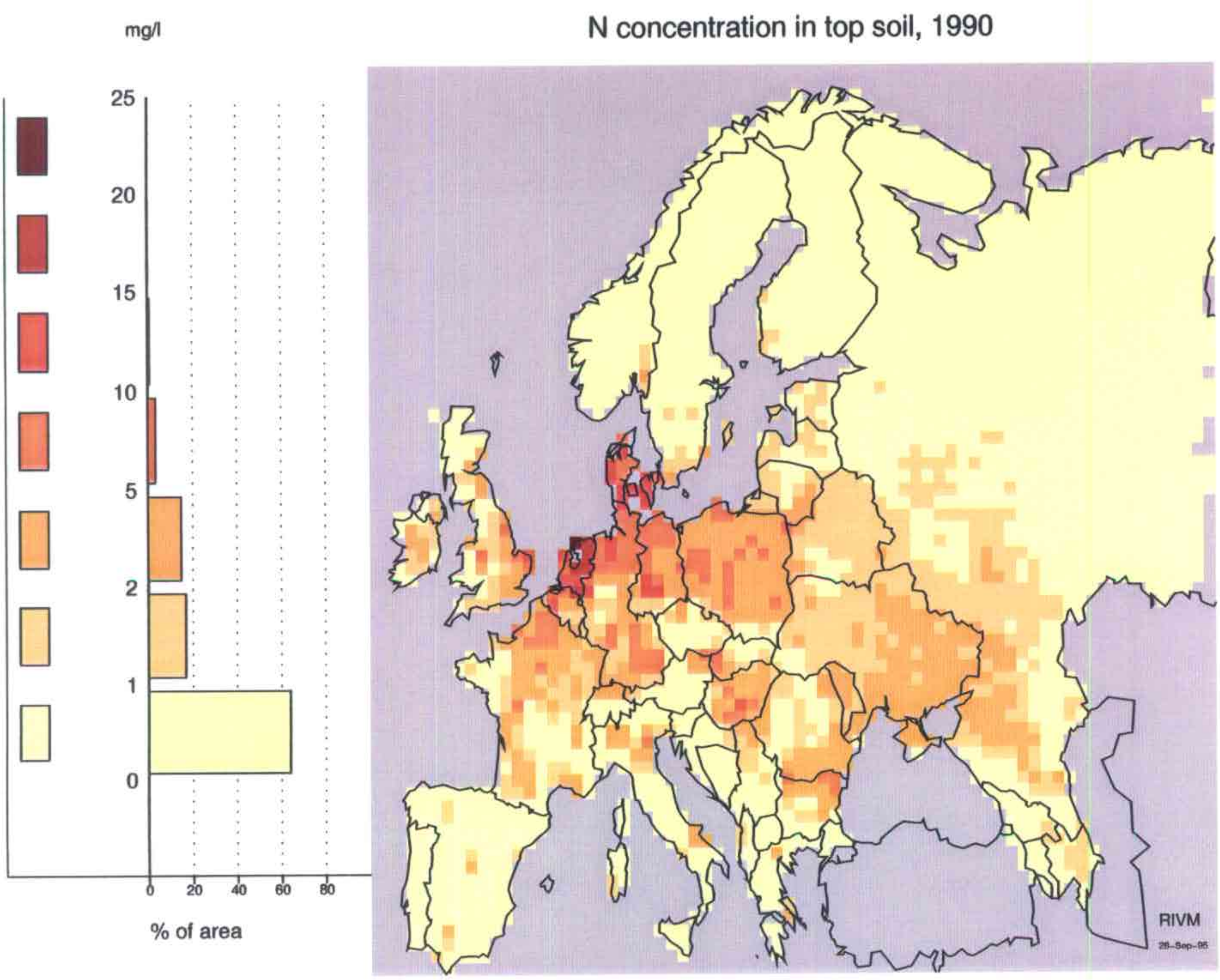


Figure 4.3 Nitrogen concentration in the ground water of the first aquifer.

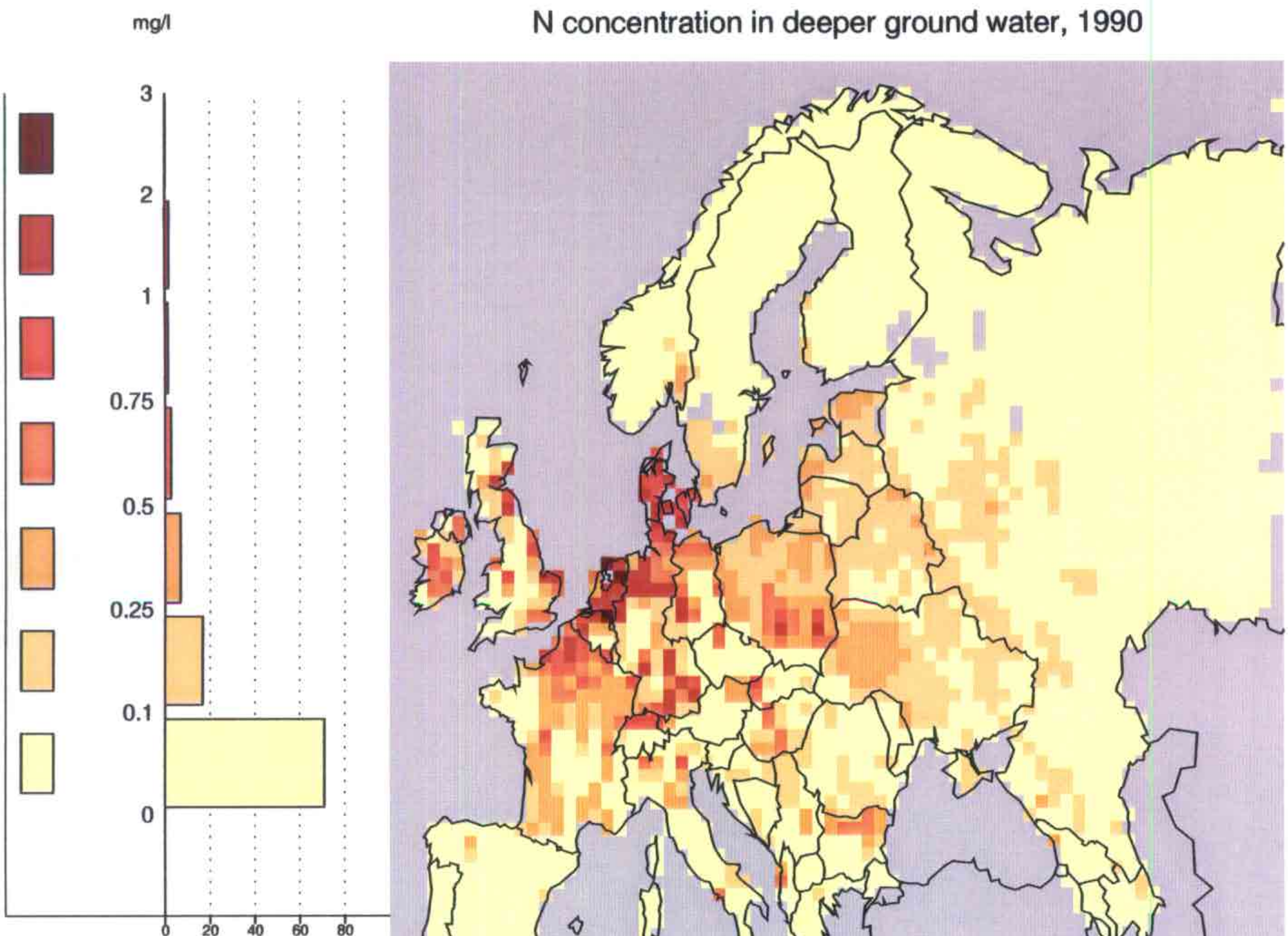


Figure 5.1 Nitrogen concentration at the mouths of the European rivers. Model calculations valid for 1990.

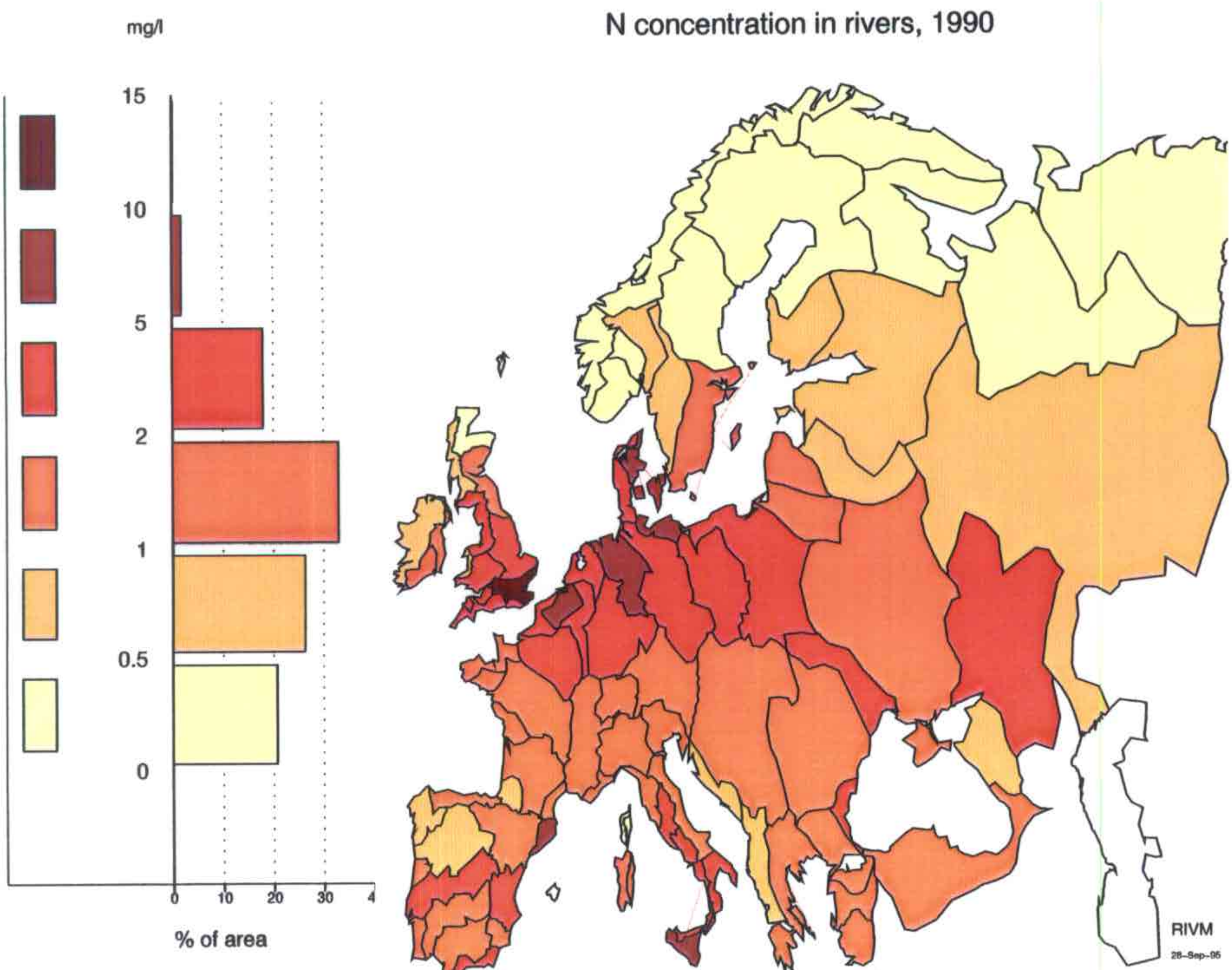


Figure 5.2 Atmospheric nitrogen deposition on coastal seas.

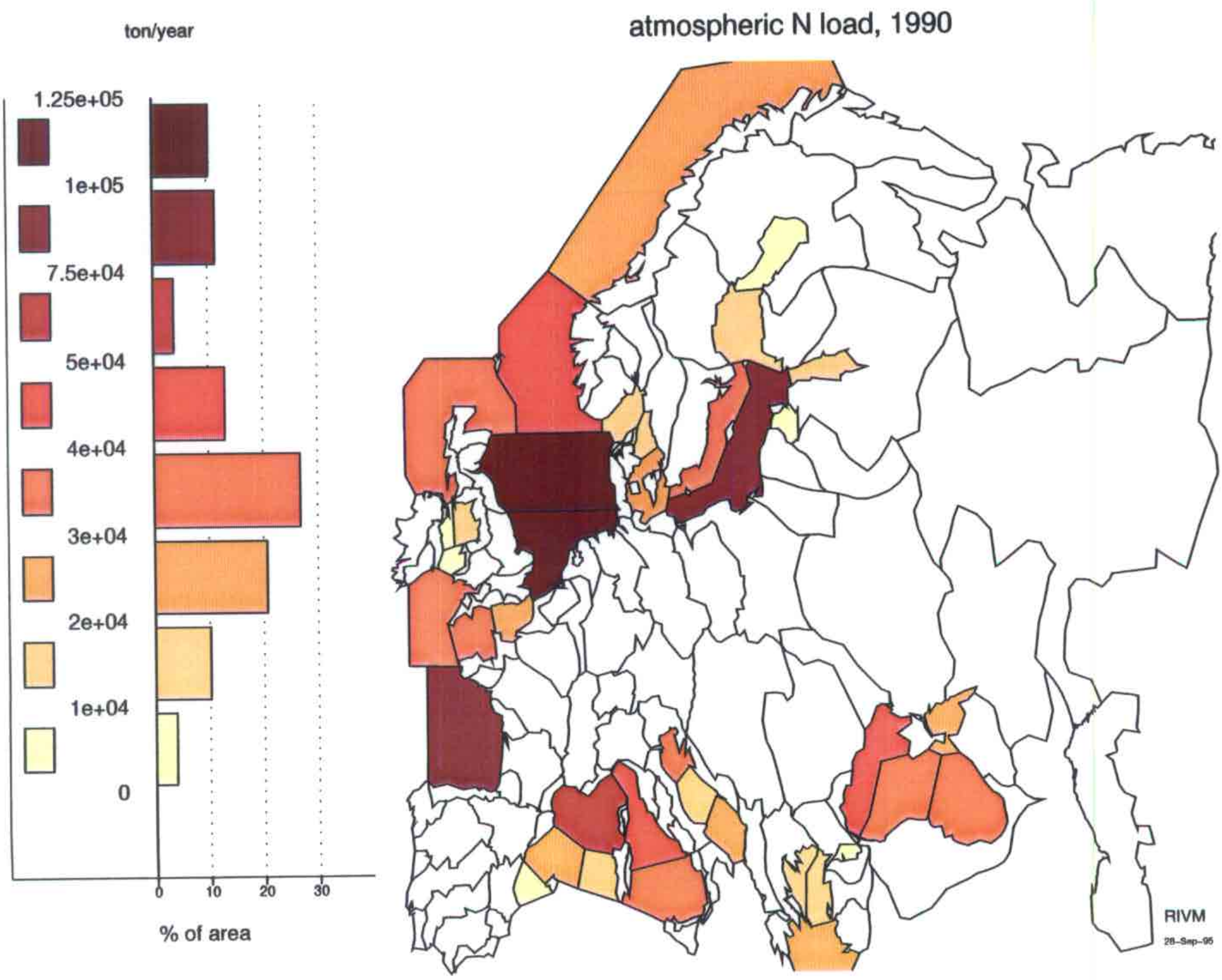
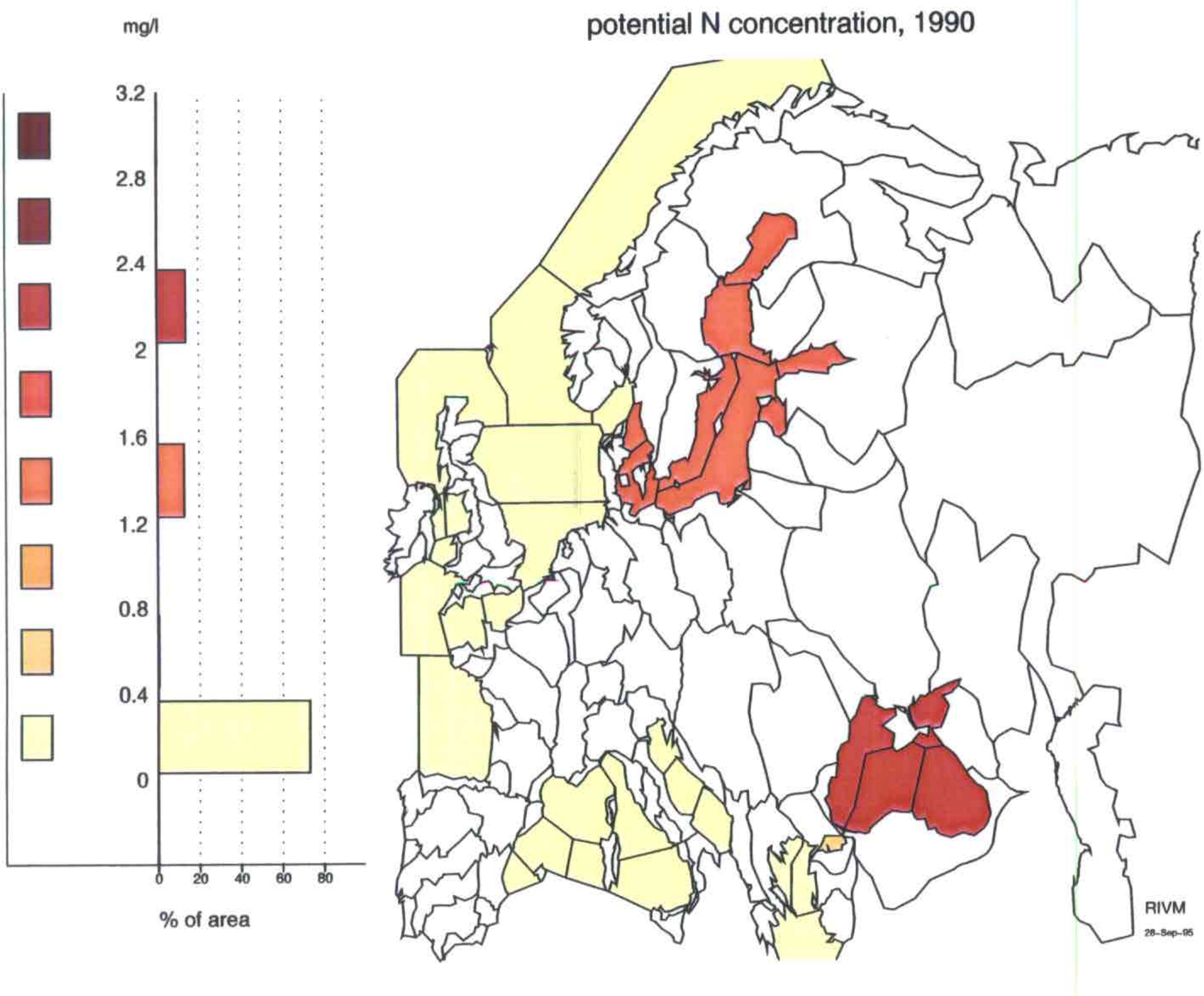


Figure 5.3 Potential nitrogen concentrations in the coastal seas.



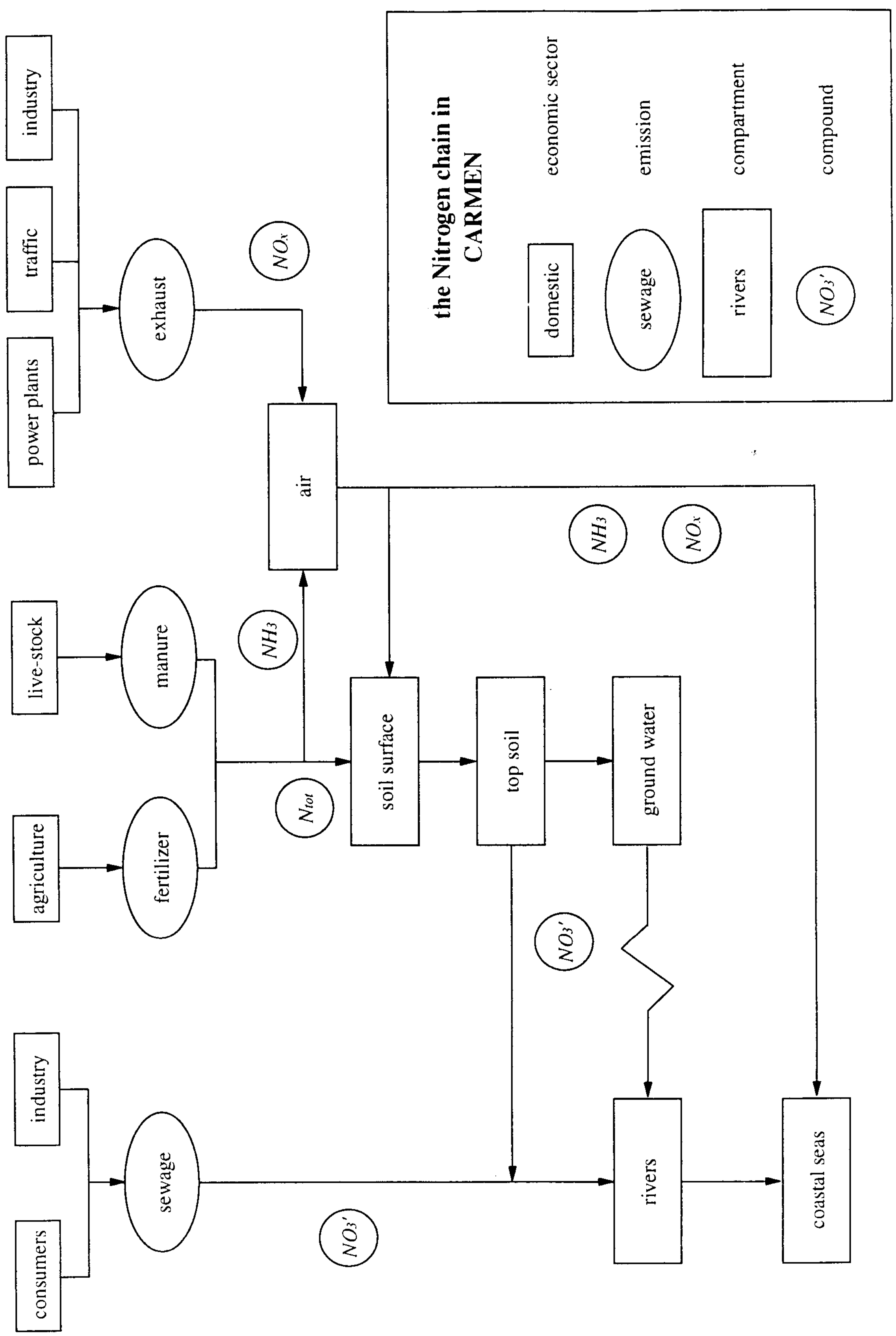


Figure 6.1

Figure 6.1

Figure 6.2 Contribution of the economic sectors to the eutrophication of the Baltic Sea.

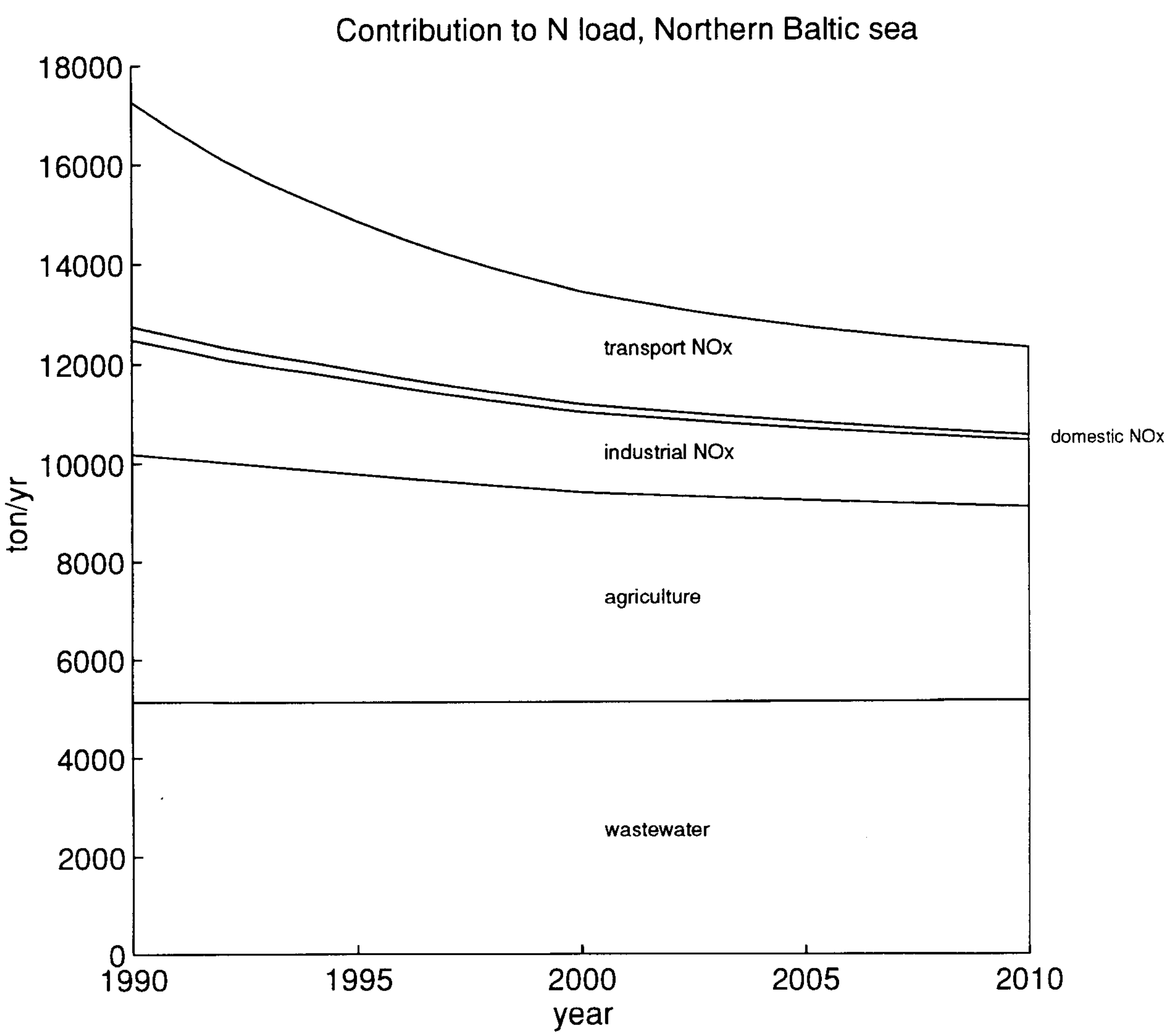


Figure 6.3 Contribution of the economic sectors to the eutrophication of the North Sea.

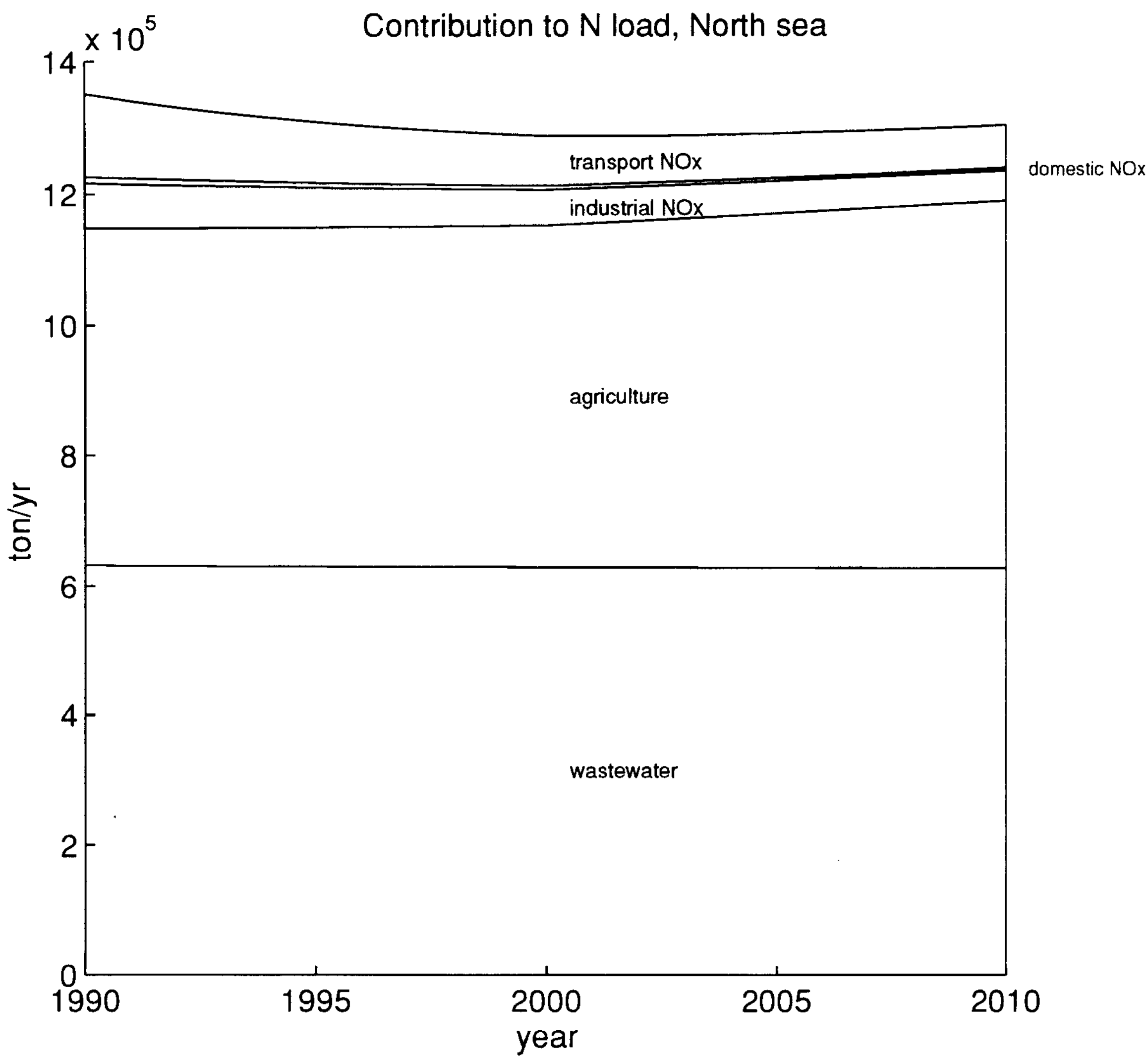
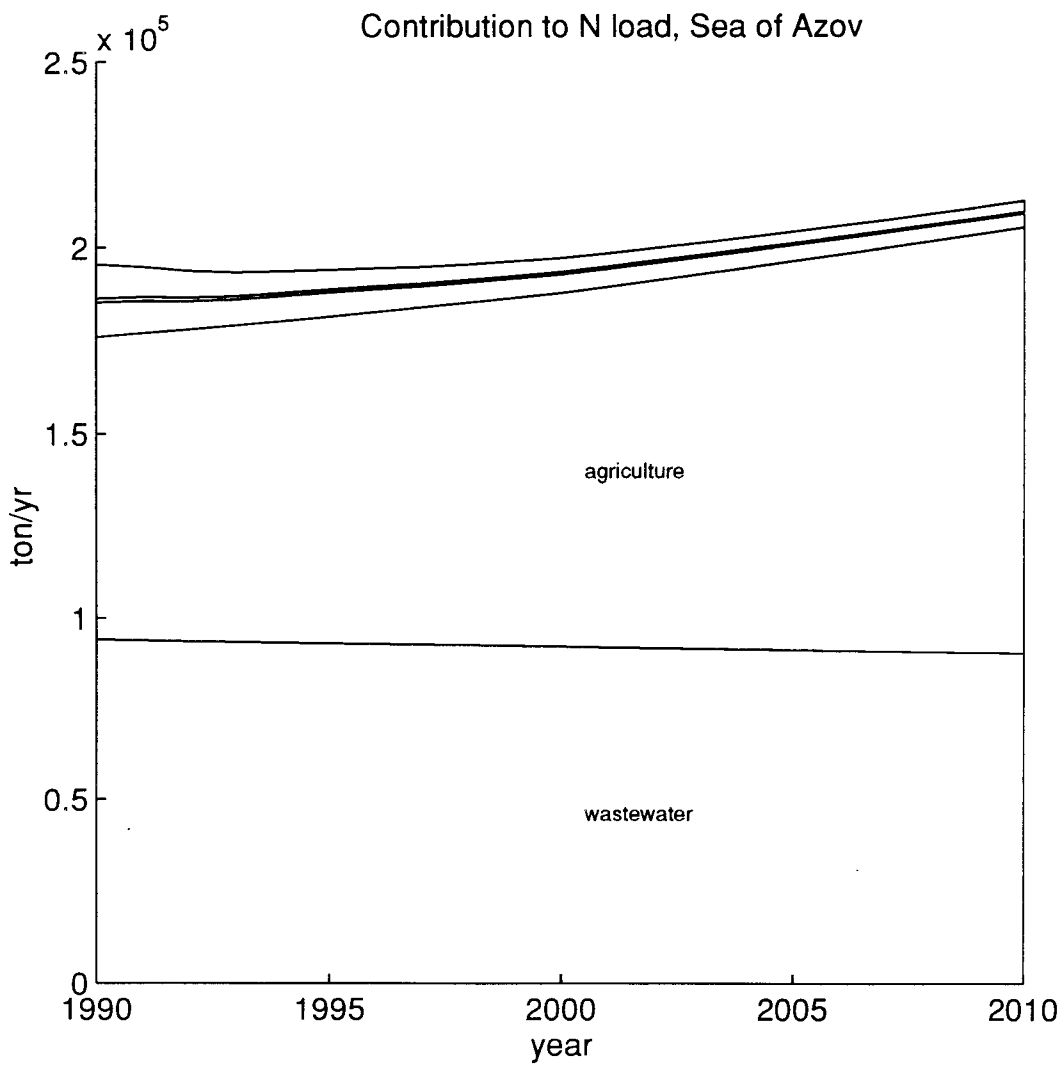


Figure 6.4 Contribution of the economic sectors to the eutrophication of the Sea of Azov.



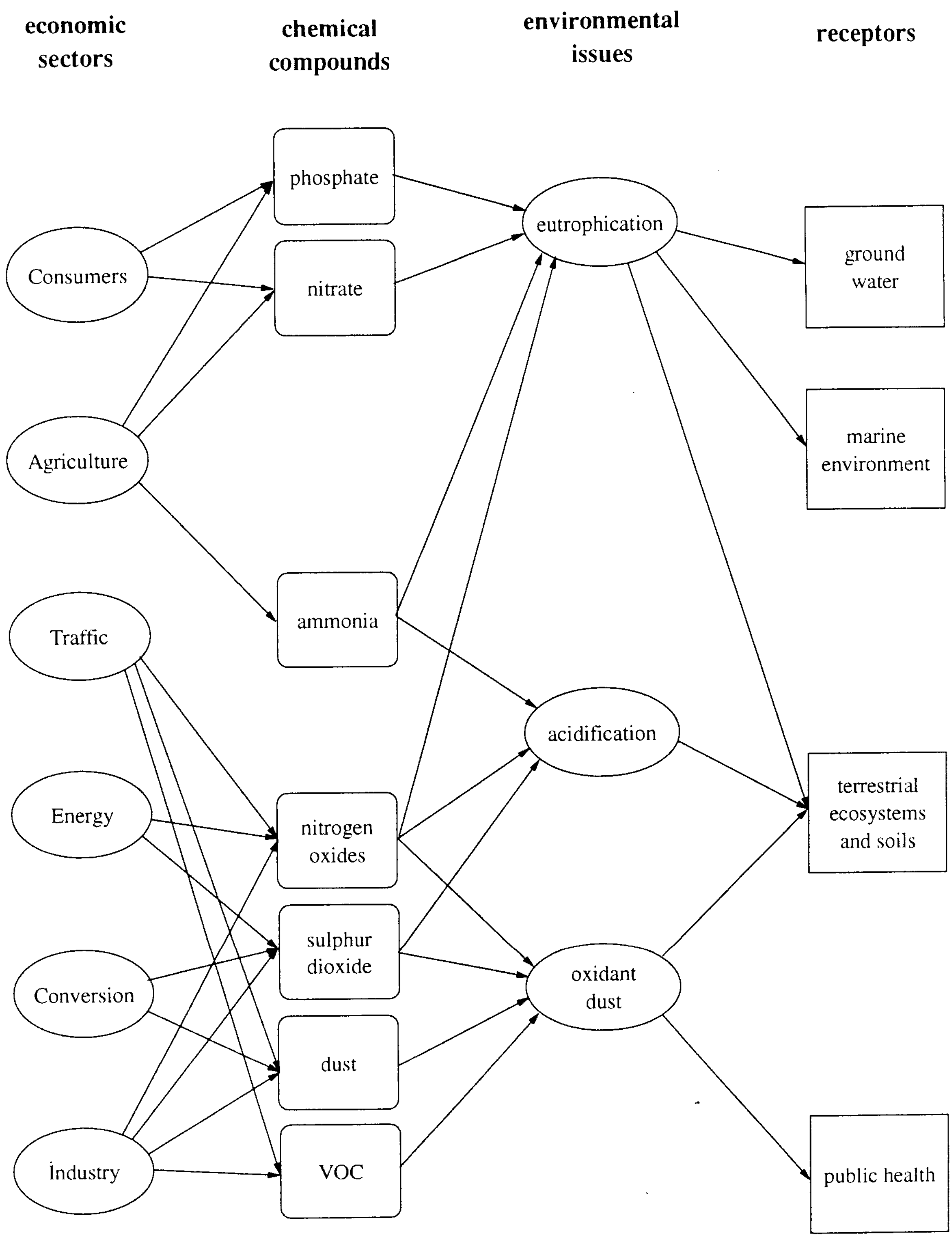


Fig 7.1 Schematic overview of the next version of CARMEN.