A NEW REGIME FOR NUTRIENT TURNOVER – *EUTROPHICATION*

9

Excessive amounts of nutrients lead to growth of algae. In small bays, algal growth may cause both a terrible sight and smell. (Photo: Katrin Österlund.)

"By changing our eating habits, we can contribute to a cleaner Baltic. Vegetables instead of beef on our plates reduces nitrogen emissions to the water. Food-stuffs without phosphate additives mean lower phosphate emissions. If we make these choices, then the Baltic Sea will continue to live, even though it will be more nutrient enriched than 20-30 years ago."

Curt Forsberg
in an interview on
the Baltic Sea eutrophication (Österberg, 1994)

Plants, and in general autotrophs, the base in all ecosystems, grow and reproduce using sunshine, water, and air. Plants get their energy from sunlight, their hydrogen and oxygen from water, and their carbon dioxide from air. In addition, however, a series of other elements, referred to as nutrients, are needed to build plant cells. Among those are the macro-nutrients: nitrogen, phosphorus, calcium, potassium, and some others. The availability of these nutrients and their flow through natural cycles determine the conditions for growth and production in ecosystems.

Nitrogen and phosphorus most often limit plant growth. In his efforts to master nature man learned in the early part of the 1900s to overcome these limitations. The addition of nitrogen and phosphorus from new sources greatly increased agricultural production. Industrial fixation of atmospheric nitrogen, the new source of nitrogenous salts, became as large as the biological nitrogen fixation. Likewise, phosphorus import from mines to biological systems greatly added to the natural fluxes from mineral weathering.

This large scale manipulation of the fluxes of these two elements has resulted in drastic environmental consequences. The added N and P in an essentially linear flow ends in water bodies and drastically changes their character as nutrient conditions change. This "eutrophication" results in massive algal growth, oxygen deficiency, and thereby a changed species composition, and change of the coastal landscape. First only rivers and lakes were influenced. Not much later the Baltic Sea, an unusually sensitive water body, became increasingly eutrophic. Today, more than a billion people all over the world, who live along coasts and depend on marine food from coastal areas, destroy these through eutrophication.

Land eutrophication also has drastic consequences on species composition. In fact what is happening *is a large scale, all encompassing change of the chemistry of land and water*. In this chapter the causes and consequences of this large scale change are discussed. Special attention is given to the Baltic Sea itself.

Boosted nutrient flows are today part of many aspects of society. Agriculture leaks fertilizers, urban areas produce sewage, car traffic as well as power plants give rise to nitrogen emissions, as do several kinds of industries, all containing nutrients that find their way to land and water. Even if the processes described are longterm and include many functions of society they may be reasonably well controlled, at least on a local level. This is demonstrated by Lake Mälaren in central Sweden, with some two million people living in the drainage basin. This lake, which was once badly eutrophied, has today once again pleasant beaches and good fishing.

In the longterm perspective "end-of-pipe" control is insufficient. Present nutrient flows are unsustainable, and have to change from linear to cyclic. Nutrients from cities, which are concentrated in sewage sludge, have to go back to farmland. Industrial nitrogen fixation has to be limited, and phosphorus mines will at some point be empty and no longer be able to provide fertilizer for farmland. This will require drastic changes in our societies.

Authors of this chapter

Curt Forsberg, use and turnover of nutrients in society, eutrophication as a global problem, eutrophication in the future; Oleg Savchuk, eutrophication of the Baltic Sea, modelling eutrophication; Lars Rydén added material on land eutrophication, and monitoring and modelling

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EUTROPHICATION

Use and turnover of nutrients in society

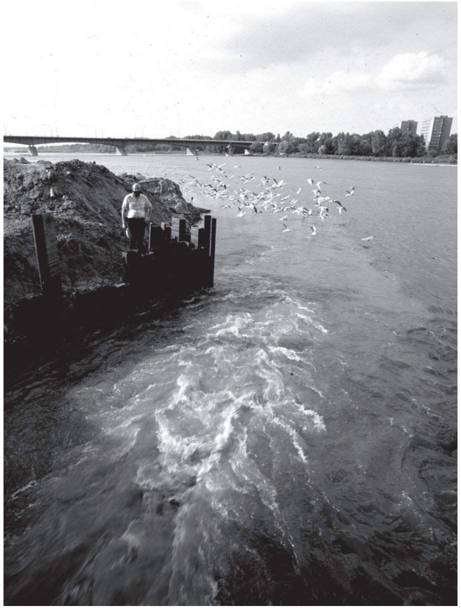


Figure 9.1. Sources of nutrients include agriculture, industry, and cities. In the early 1990s non-treated sewage, rich in nutrients, flowed into the Wisla river from Warsaw, the capital of Poland. Today, wastewater treatment has dramatically improved in all cities in the region. (Photo: André Maslennikov.)

Use of nutrients – from small and closed to large and open systems

Nutrient dynamics between land and water have changed greatly due to the development of modern industrialized society. In pre-industrial time, nutrients, largely nitrogen (N) and phosphorus (P), were cycled within a high-diversity ecosystem which included humans. "Manure was gold," and the system was a nearly closed one, with little export to the surroundings. Agriculture developed and new regimes were invented to extract nutrients from meadows and wetlands through increased biological fixation (Chapter 7).

As industrialized society developed so did the export of crops, that is food – including nutrients – from rural to urbanized areas. This gave rise to a net loss of nutrients which, during the last part of the 1800s, was compensated for by the import of guano from South America. Nutrients in human excrement were partly used on farmland in the vicinity, but primarily ended up in lakes and rivers via sewage systems.

Because the imported nutrients could only be applied once, the store of guano was rapidly exhausted. However, at the time for the First World War, an industrial technology for fixation of atmospheric nitrogen, the Haber Bosch process, was invented and a powerful scheme for the production of nitrogen compounds was established. This linear flow of nitrogen from the atmosphere to the environment had to be powered by large amounts of fossil fuel.

In parallel, mining and trade with raw phosphate created a new, large flow of phosphate from fossil sources to fertiliser manufacturers. Via agriculture to urban areas, this phosphate ended up, as the nitrogen, in inland and marine waters. Since the mid-1950s, great amounts of phosphate have also been transferred to water as phosphate-containing chemicals, for example detergents. What was earlier a nearly closed system for phosphorus turnover was rapidly transformed into an open one with low retention and high export. The linear flow of phosphate, from the fossil stores to marine sediments, means that phosphate management of today is not sustainable, considering that phosphate is a limited natural resource.

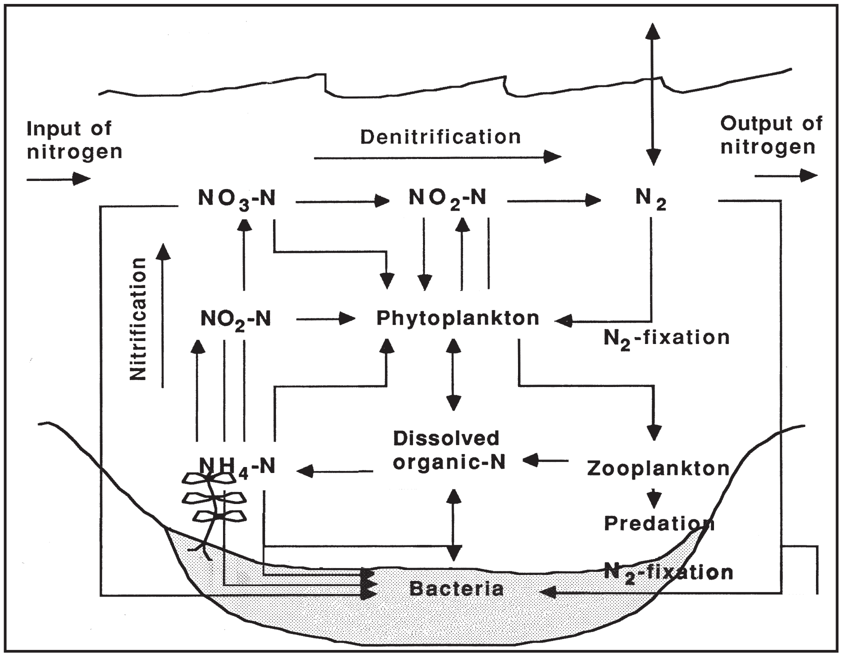
Since World War II, industrialized society has produced an accelerating surplus of nitrogen compounds which have been emitted and introduced into different terrestrial and aquatic ecosystems, including the Baltic Sea. Three main types of human activity are responsible for these increased emissions: discharge of sewage, run-off from modern agriculture (including livestock farming and forestry), and finally combustion of fossil fuels and firewood.

The increased fluxes of nitrogen have contributed to a number of environmental problems, in particular:

- nitrogen increase in surface water, stimulating eutrophication,
- nitrogen saturation in soil, resulting in soil eutrophication and leakage of nitrogen,
- acidification of soil and inland waters, chiefly as a result of soil acidification in the catchments,
- global warming, and
- thinning of the stratospheric ozone layer.

Nutrients are organic and inorganic chemical compounds or elements necessary in various amounts to support normal living processes. Inorganic nutrients are circulated between organisms, that make up components of an ecosystem, and stored in the atmosphere, lithosphere, and hydrosphere.

Figure 9.2. A simplified nitrogen cycle. The turnover of nitrogen in water shows the relationships of different forms of nitrogen with the growth of bacteria, and phyto and zooplankton.



Comparison to natural fluxes of N and P

Let us briefly, as a contrast to the flows of N and P through the technosphere, regard the natural flow of these elements, the *bio-geo-chemical cycles* of nitrogen and phosphorus (Chapter 2). This concept is essential for the understanding of the balance of these elements in nature.

Nutrients enter the biota as plants assimilate them, most often as simple inorganic ions. Nitrogen is easily available in the forms of nitrite, nitrate, or ammonium (respectively NO_2^-, NO_3^-, NH_4^+), and phosphorus is taken up, mainly as phosphate. Both elements also occur in different organic forms, e.g., nitrogen in amino acids, and can as such be utilised by algae. In addition, several bacteria, including blue-green algae, also called cyanobacteria, have the ability to use atmospheric nitrogen, N_2, through *biological nitrogen fixation*.

Nitrogen (Figure 9.2) and phosphorus (Figure 9.3) are added to terrestrial and aquatic ecosystems in different ways. Nitrogen by atmospheric wet (gaseous) and dry (particulate) deposition, and by biological nitrogen fixation. Phosphorus is added mostly by mineral weathering. Nitrogen is recycled back from water to the atmosphere by the process of *denitrification*. There exists no similar return process for phosphorus. This element "travels" through ecosystems in one way only; namely from soil to surface waters and ultimately to the sea. It is only as the sediments are converted into minerals and again, after geological time, are exposed to weathering or volcanic activities that its cycle is complete.

Man-made inputs of these nutrients have increased dramatically during this century due to three main processes:

- use of artificial fertilisers,
- use of synthetic detergents, and
- combustion of fossil fuels and firewood.

The first two of these have there origin in *industrial nitrogen fixation* and phosphate mining, while combustion gives rise to nitrogen oxides from atmospheric nitrogen in the oxidation process. These inputs caused by man are considerable. Industrial N-fixation alone is on a world scale larger than the biological one. It is thus not surprising, that a turnover of these elements which has increased by more than two, gives rise to serious environmental effects.

Nitrification is a bacterial processes in which, in aerobic conditions, ammonia (NH_3) is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-).

Denitrification is a bacterial processes, occurring in anoxic conditions, i.e. in bottom waters, in which nitrates (NO_3^-) are converted to nitrogen gas (N_2) which is released to the atmosphere.

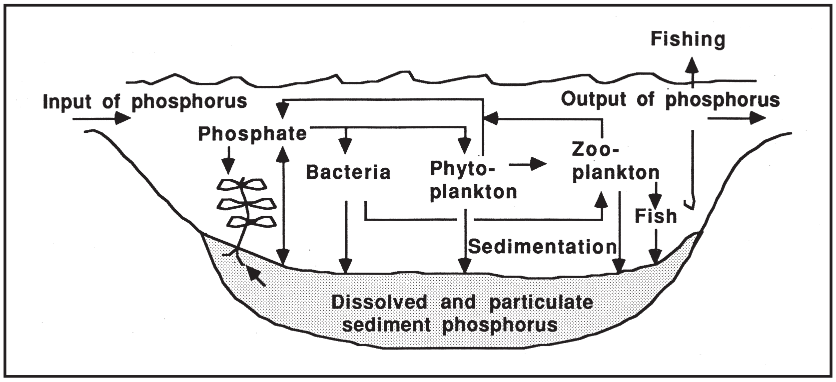


Figure 9.3. A simplified phosphorus cycle. The turnover of phosphorus in water shows the relationships between phosphate and the growth of bacteria, and phyto and zooplankton.

Biologically bound N and P move through cycles in several ways. Plankton algae and other organic matter which are not grazed or degraded in the water column sink to the sea bottom. There it is gradually decomposed, or mineralized, by bacteria, resulting in a release of phosphate and ammonium. Other bacteria can oxidize ammonia (NH_3) to nitrite (NO_2^-) and nitrate (NO_3^-), a process called *nitrification* (Figure 9.2). Nitrification is, in contrast to denitrification, an aerobic process. The inorganic nutrients can return to the water, be assimilated, and again support primary production. A corresponding local cycle occurs in terrestrial ecosystems where the same bacterial processes take place in the soil.

A considerable amount of phosphorus may become ”fixed” in the sediments, often bound to iron, where it effectively stays outside the biological cycle. However, in different biochemical processes large amounts of phosphorus may be released from the sediments. This may occur under anoxic conditions in deep water and on shallow, eutrophied bottoms at high summer temperatures. This release of phosphorus is often called *internal loading* and is a result of long-term nutrient input. Internal loading supports eutrophication, and can cause high primary production even after a substantial reduction in external loading.

Normally, the surface material in a sea sediment is oxygenated. Reduced, anoxic, conditions prevail a few centimetres or less below the surface. The boundary between these oxic and anoxic environments is called the *redoxcline*. Here large quantities of bacteria convert nitrate (NO_3^-) to nitrogen gas (N_2), in denitrification. This occurs also in anoxic bottom water, e.g., in the deep water of the Baltic Sea. The nitrogen gas is released into the water column and further to the atmosphere.

Phosphorus lacks a gas phase and can only be assimilated in one inorganic form, namely phosphate. Cycling of phosphorus in the water column and in the soil is therefore less complicated than that of nitrogen. Phosphorus interactions between sediment and water, however, may be very complicated due to microbial and physico-chemical processes.

Nitrogen and phosphorus in agriculture

The main consumers of nitrogen and phosphorus in most countries are the agro-ecosystems, which import these nutrients in fertilisers, fodder, sludge, food products, and in chemicals, e.g., washing products. The consumption of fertiliser P, has varied substantially during this century. In the early 1900s about 15,000 tonnes of P were distributed on arable land in Sweden. The consumption increased to about 25,000 tonnes at the end of the 1930s. A marked drop occurred during World War II, followed by a large increase reaching a maximum of more than 70,000 tonnes in 1974. Thereafter the consumption declined. In 1999 the total use of P in Swedish agriculture was 48,000 tonnes or 20 kg/ha. Expressed as kg per ha of arable land, the input of N and P at the end of 1999

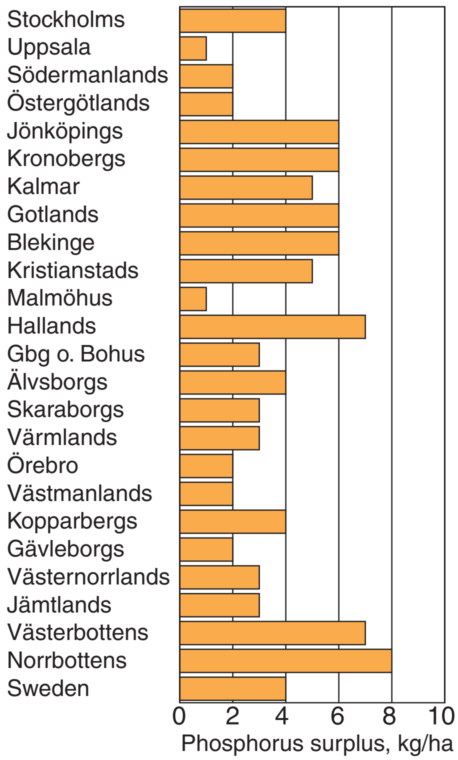


Figure 9.4. Accumulation of phosphorus in arable soil (annual surplus in soils in kg per ha during 1995). The values for all 24 counties in Sweden show several-fold differences depending on the crop and character of the soil. The largest values are found for the least productive counties in the north (Norrbotten) and lowest in the most productive counties in the south (Malmöhus). (Source: Statistics Sweden, 1996.)

was 130 and 40 kg respectively (Statistics Sweden, 2002). A total of 95 kg N and 20 kg P per ha was artificial fertilisers, the rest manure.

Accumulation of N and P in soil will occur when the yearly addition of fertiliser nutrients exceeds what can be removed with the crop at harvest. Phosphorus balances for Swedish agro-ecosystems show high figures for P-accumulation (Figure 9.4). Thus, on a national level for a period in the mid-1980s, Swedish agro-ecosystems accumulated about 50% of the P input (Bollmark, 1991). Peak values for yearly accumulations of 60% or more have been reported (Forsberg & Wallsten, 1986). Surplus application of P is not unique for Sweden. Eight West European countries indicated for the period 1984-86 yearly P accumulations between 25-73% of the input, with a peak value for the Netherlands, where almost 3/4 of the phosphorus input was left in the soil when the crops were harvested (Bollmark, 1991).

In the early 1990s differences between input and output of N and P in Swedish agriculture show a removal by harvest with 80 kg N and 14 kg P per ha. The differences between input and output gives a surplus of 42 kg N and 4 kg P per ha. The nitrogen surplus leads to leaching (20 kg per ha), denitrification, and built-up in soil. The surplus P is mainly built-up in soil (Statistics Sweden, 1995b) (Figure 9.5).

The magnitude of losses of nutrients from agriculture is dependent on many factors, e.g., the intensity of cultivation, soil conditions, runoff water, wind, temperature and snow cover (Svendsen & Kronvang, 1991). The dominating P transport out from a watershed occurs with runoff water and erosion, while leaching and groundwater transport usually contribute with smaller amounts (Tiessen, 1995).

The losses of N and P from agriculture to the environment are considerable. In Denmark the contribution of P from agriculture to the Baltic Sea has been estimated to be 21-23% of the total P leakage. The corresponding figure from Sweden is 13%. The overwhelming part of this comes from arable land. Phosphorus is transported mainly as surface runoff bound to soil particles or with drainage water in dissolved form. Phosphorus losses occur irregularly mainly during episodes with heavy rain on frozen soil. It may be quite difficult to measure the phosphorus leakage, but a value typical for Sweden is around 0.5 kg per ha and year (Figure 9.5).

The relevance of P losses from agriculture, as well as from other man-made P sources, is evident when comparing the size of losses with those from unfertilised forest areas. In the Nordic countries these background (forest) values generally are in the range of 0.04 – 0.12 kg P per ha and year, and principally they are increasing with increasing amounts of runoff water. Swedish agriculture enhances the natural P discharge by a factor 10, giving a P loss interval of 0.3 – 1.0 kg per ha and year (Svendsen & Kronvang, 1991, and references therein).

Enhanced concentration of P in groundwater may in time be expected underneath soil layers enriched with P. Simple percolation experiments demonstrated that different soils lost about 15% of the total P when rainwater passed through these soils (Rydin & Ottabong, 1997). Long-term application of manure and fertilisers showed that P may reach the groundwater, especially in areas with shallow water tables (Eghball et al., 1996). In the Netherlands the P content in groundwater is anticipated to increase by up to 100% in a near future (Lijklema, 1994), depending on the high accumulation of P in agriculture.

Besides the non-point sources, contributions from animal stables, countryside farm sewage, silage, detergents in milk handling, etc., all considered to be point sources of P, may be significant components of the total losses from farm districts.

Increased use of agro-chemicals has created environmental problems, not only in the form of eutrophication of recipient waters, but also degradation of groundwater quality, in some places leading to toxic levels of nitrate in wells. The magnitude of this impact is ultimately dependent on the local climate, soil

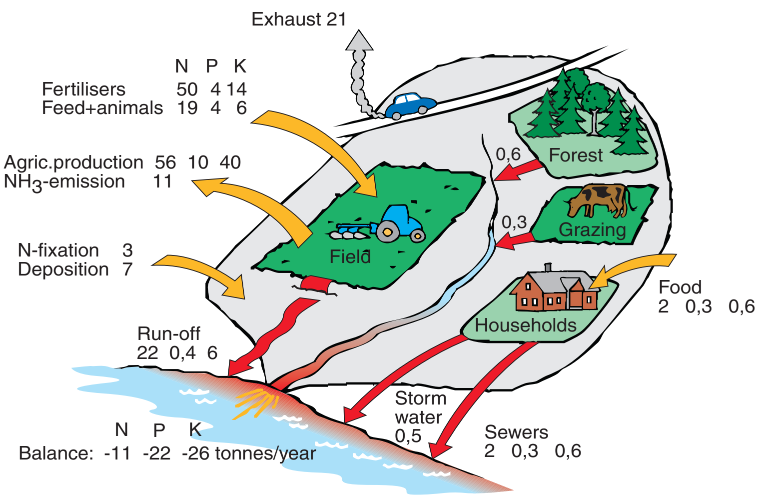


Figure 9.5. Plant nutrient fluxes in a watershed. The values refer to fluxes of nitrogen (N) phosphorus (P) and Potassium (K) in tonnes per year in a watershed in south Sweden. Runoff contains 24 tonnes N and 0.7 tonnes P and 7 tonnes of K. In addition emission of ammonia contributes 11 and car exhausts an additional 21 tonnes of N. (Source: Jakobsson et al, 2000.)

type and agricultural conditions. An important aspect of the leakage of nitrogen is the improper use of manure, which accounts for a major part of the leakage. Spraying relatively large amounts of manure over small areas, in combination with frozen soil, is the main reason for this. The losses of nitrogen from agriculture are larger than those of phosphorus.

Nutrient flows in urban areas – waste water treatment

From agriculture and industry nutrients are exported into urban areas with food products and chemicals. The Swedish consumption per capita and day is about 14 g N and 2 g P. More or less similar values characterise other countries in the Baltic Sea region. After consumption, the nutrients are transported to sewage treatment plants, discharged directly into the recipient water, or accumulated in organic household wastes in landfills. After sewage treatment the nutrients are enriched in sludge. The P concentrations in sewage increased dramatically after the introduction of phosphorus-containing detergents for washing in the mid-1950s. Today, in many countries these products contain no or low amounts of P.

Municipal waste water is an important source for discharges of nutrients into recipients, such as lakes and rivers, and finally into the Baltic Sea. In the beginning of this century sewage systems were installed in some cities, mostly for sanitary reasons. As urbanization proceeded the harmful effects of sewage on the recipients became evident and the sewage was led to sewage treatment plants (Chapter 17). From a simple start with only mechanical treatment, many plants have been equipped with both a biological step for removal of organic material and a chemical step for phosphorus removal. Recently nitrogen removal has been introduced in some treatment plants in Sweden.

As P was identified as a key element in lake eutrophication the interest was early focused on P removal in sewage. This treatment is now regarded as standard in some countries or in areas sensitive to eutrophication. Parallel to enlarged and improved sewage treatment, *the volumes of P-enriched sludge have increased substantially*. However, for technical, practical, environmental, and economic reasons it is difficult or impossible to effectively recycle the sludge-bound phosphorus from towns to farm land. Great volumes of sludge are therefore annually deposited in landfills, directly or as ash after incineration. During the mid-1980s about 60% of the sludge produced in Swedish sewage treatment plants was delivered to agriculture (Bollmark, 1991). Three years later the corresponding figure was only 35% (Statistics Sweden, 1990). Return of sludge to farmland is still on a low level. The reason for this reduction was a debate on health effects of hazardous elements included in the sludge,

Table 9.1. Total balances of nitrogen and phosphorus in Swedish farm fields during 2 years, 1995 and 1997. (Source: Statistics Sweden.)

Category	Nitrogen kg/ha		Phosphorous kg/ha	
	1995	1997	1995	1997
commercial fertilizer	71	70	7	7
horse manure	25*	25	8*	8
field manure	15*	15	2*	2
sowing	2	2	0.3	0.3
deposition	11	9	0.3	0.3
sludge	1	1	0,7	0,7
nitrification	10	11	-	-
Total	134*	132	18*	17
Removal:				
harvest	83	86	13	14
harvest residuals	2	2	0,3	0,3
Total of harvest products	85	89	13	14
Surplus:				
ammonium from plants	2	2	-	-
leakage	27	27	0.3	0.3
denitrification, establishment, etc.	21*	15	5	3
Total	50*	44	5*	3
Furthermore:				
ammonium from commercial, horse, and field manure	16	16	-	-

* = Revised figures

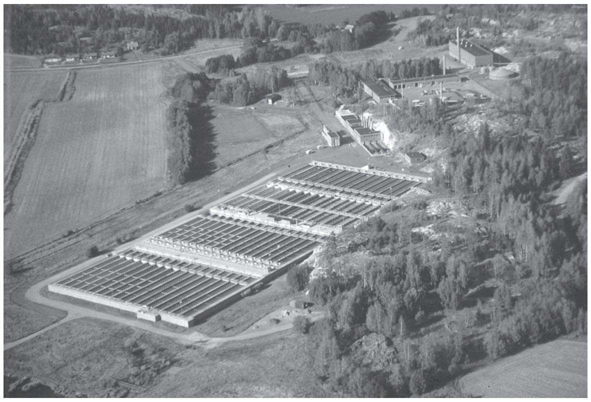


Figure 9.6. Wastewater treatement plant. Himmerfjärden treatment plant south of Stockholm serves 250 000 person equivalents. The reservoirs seen here is used for biological and chemical steps in which organic matter and phosphorous in the wastewater is reduced dramatically. More recently a step to reduce nitrogen has been added in many Swedish treatment plants. (from A. Cronström, 1988.)

especially heavy metals but also some organic chemicals, for example pharmaceuticals. Nonetheless, the large volumes not reused have focused interest on phosphorus accumulation and retention in urban regions.

The first *P balance for an urban region* served by phosphorus removal from sewage was calculated, using central parts of the city of Stockholm as a model. This balance, valid for 1990, includes 920,000 people served by four sewage treatment plants (Forsberg & Rengefors, 1993). The results show that approximately 80% of the phosphorus was accumulated in the sludge. In 1997 more than 60% of the sludge could be reused on arable land or for soil conditioning outside agriculture. Sludge accumulation may in principle, be similar in most urban areas, especially in densely populated ones. This is, however, not a longterm solution. Over time the increasing accumulation may be expected to lead to increasing losses of P. Leakage may be described as a von Bertalannfy process (Odum, 1983), where in time losses may be proportional to the amounts stored. Phosphorus removal from sewage may, therefore, lead to a change from municipal point sources to non-point sources of phosphorus to the environment.

The direct discharge from municipalities into the Baltic Sea accounts only for 10% of nitrogen and 15% of phosphorus, figures that are even smaller for industry. But to these figures should be added the considerable discharges from urban areas into rivers in the drainage basin, and finally to the Baltic Sea. Sewage is the main source of phosphorus emissions to the Baltic Sea. The technical standard of sewage treatment plants shows great variation in the Baltic Sea region. Many municipalities, especially in the eastern part of the area, have no sewage treatment at all, but this situation will change as a great number of treatment plants are planned. On the western side of the Baltic Sea the situation is different with a large number of advanced treatment plants for P removal.

Control of the flux of P with phosphorus removal from sewage, means growing volumes of P-enriched sludge. Where will all this phosphorus in sludge go in the future (Figure 9.7, a-e)? In industrialized society, P is imported to agricultural (a) and urban (b) areas. P is lost by erosion to drainage water (c), urban storm water, and leakage in sewage systems (d). At sewage treatment plants for P removal, > 90% of incoming P can be bound in sludge. The residue is discharged directly to the recipient water (e).

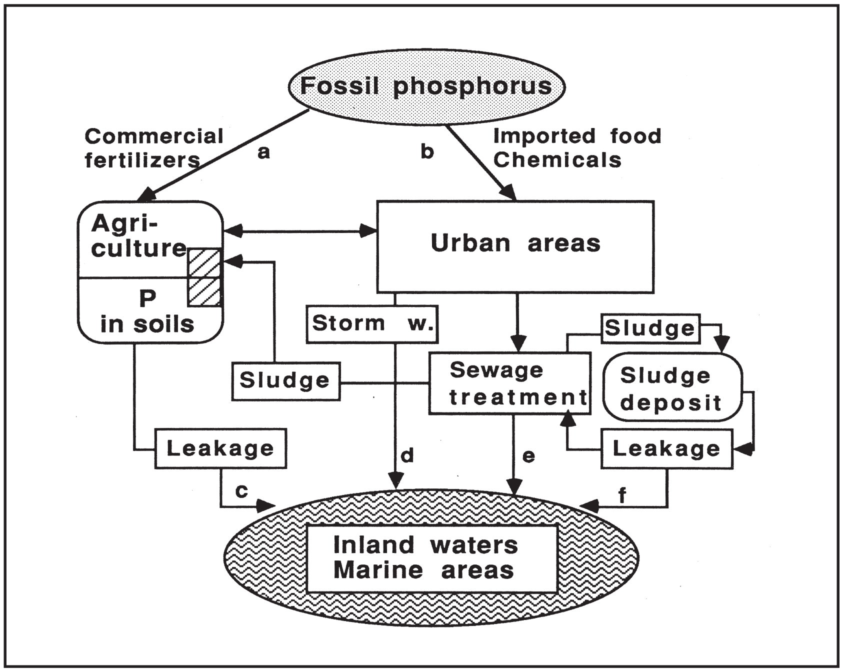


Figure 9.7. The open flux of phosphorus in modern society. Fossil phosphorus (P) flows in the society to urban areas (a) and agriculture (b) and from these areas to water (c, d, e, f). Dynamic equilibrium in P-flux is established when a + b = c + d + e + f. Prior to that, phosphorus will be stored in soils and deposits.

The possibilities to recycle phosphorus in sludge are limited by several difficulties. When the sludge can be used in agriculture, transport costs restrict distribution to areas near the treatment plants. Due to pollution by heavy metals and toxic organic compounds, increasing amounts of sludge must be deposited, resulting in a growing storage with leakage as a consequence (f). The degree of leakage of P from sludge deposits will mainly depend on the volume of percolating water and the redox conditions. A release as high as 95% could be observed from anaerobic P-enriched sludge (Rydin, 1995). With increasing accumulation, an increasing loss may be expected with leakage proportionate to the stored amounts. With time, the system will reach a dynamic equilibrium, where the import (a + b) equals the export (c + d + e + f). At that time, sewage treatment systems may essentially not have a function any longer, as point sources of phosphorus have been transformed to non-point sources. The further movement of phosphorus will to a high degree be regulated by the soil systems, as phosphorus often is effectively bound in certain oxidized soils, at least up to the level of saturation.

Recently, promising methods have been developed for recovering phosphate from waste waters and animal manure, e.g as calcium or magnesium ammonium phosphate, which can be used by the phosphate industry. Full scale plants are already working. The first ones in Sweden are under construction.

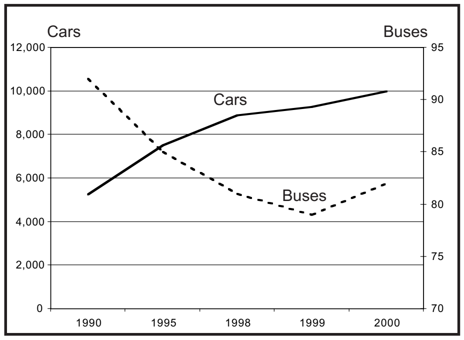


Figure 9.8. Number of cars and buses in Poland between the years 1990 and 2000, in thousands of vehicles. (Source: Polish Official Statistics: http://www.stat.gov.pl/english/)

Traffic and the energy sector

A considerable amount of nitrogen from non-point sources is derived from car exhausts and the burning of fossil fuel as well as biomass for the production of energy. The combustion process leads to oxidation of nitrogen in the air to produce a mixtures of oxides, collectively denoted as NO_x, or nitrous oxides. Together with water in the air these constitute the very strong acids, nitrous acid and nitric acid. The exhausts thus both eutrophy and acidify the soil and water where they are finally deposited. Some of the nitrous oxides also contribute to the enhanced greenhouse effect as well as the destruction of the stratospheric ozone layer (see further Chapters 10 and 11).

Combustion leads to a substantial atmospheric deposition in inland waters and the Baltic Sea. The values for ship traffic and air traffic are not well known but the contribution from ship traffic is believed to be considerable.

The development of car traffic is strong, and the number of cars is increasing in the whole Baltic Sea region. In the European Union there is on average about 455 cars per 1,000 inhabitants (1998). In Poland, the figure for the year 2000 was about 259 cars per 1,000 inhabitants, which can be compared with 60 in 1980 (Tengström, 1994).

Figur 9.9. Car exhausts and other combustion processes is a major source of eutrohying nitrogen as NO_X. Car traffic is rapidly increasing in Central and Eastern Europe, as here in Gdynia, Poland. (Photo: Lars Rydén.)

Figur 9.10. Buffer zones reduce nutrients. Buffer zones are the strips of bushes and other vegetation between fields and water. They reduce water flow and allow some of the nutrients to be used in growth of biomass. The traditional landscape often contained such buffer zones, as here in the Kashubian area in north Poland. (Photo: Lars Rydén.)

With the installation of catalytic converters in cars, a reduction in emissions of nitrous oxides is achieved but it is only limited, as simultaneously the number of cars is growing. Alternative developments that would lead to decreased amounts of car exhausts, such as increased use of electric cars, or a decrease in use of cars in general, does not seem to be within sight. Therefore, within the near future, great reductions in emissions of nitrogen and carbon dioxide can not be expected from road traffic in the Baltic Sea basin.

Figur 9.11. Wetlands reduce nutrients. Agriculture is a major souces of nutrients carried by runoff from fields. In wetlands the nitrogen is retained through denitrification, and phosphorus by precipitation. Reduction of wetlands have increased the eutrophication problem. (Photo: Lars Rydén.)

Influence of landscape changes – wetlands

The transformation of a traditional agricultural society into a modern industrialized country has in itself several consequences that lead to changed turnover of nutrients and increased leakage to water recipients. We have already seen that urbanization leads to high demands on sewage systems in municipalities and that industrialized agriculture and animal production give rise to leakage of nitrogen and phosphorus. A further change is the turnover of former wetlands into agricultural areas, as well as the changes in rivers and installation of drainage systems for fields. The traditional and more natural landscape is transformed into an efficient agricultural area. Natural processes of nitrification and denitrification occurring in wetlands are lost in these changes. In Sweden and Denmark, a considerable percentage of the former wetland areas have in this way been transformed, while the process has not gone as far in the countries on the eastern shore of the Baltic Sea.

Rather few estimates of the amount of nitrogen removed by passing through wetland areas are available. In the northern countries, the annual removal can be assumed to be small as denitrification may be less efficient at high water flow (short water-residence time) occurring when temperature is low, in spring and autumn. Recent estimates indicate a removal of 10-15%. If nitrogen is assimilated by green plants, harvest of biomass may remove much more nitrogen.

A considerable interest is currently directed towards the possibility of reducing nitrogen in leakage water by draining into small brooks and rivers that have an original shape, with meanders and shallow passages, as opposed to drainage tubes and man-made rivers with even sides. A further possibility of increasing nitrogen removal is offered by so-called ecotone areas, i.e. stretches of non-cultivated land with bushes or other vegetation, between fields and streams or lakes. The transformation of rivers to improve nutrient turnover, called river management, has caused considerable interest in e.g. Denmark and Poland. The construction of artificial wetlands for nitrogen removal is also important in e.g. Sweden.

Eutrophication – a global problem

Eutrophication means well nourished

Eutrophication was first identified as a common phenomenon in freshwater ecosystems. It is a natural process in which nutrient poor (oligotrophic) lakes are slowly transformed into nutrient rich (eutrophic) lakes, a process which normally may take thousands of years. Due to human activities, however, eutrophication has been accelerated ("man-made eutrophication"), and is nowadays a world-wide problem, including in large marine areas around the world.

Literally, *eutrophic* means well-nourished. *Eutrophication* refers to natural or artificial addition of nutrients to water bodies or land areas and to the effects of nutrient inputs. There are many definitions of the term "eutrophication." Here we will use the definition and the delineation of the problem as presented by Richard Vollenweider (1992), one of the leading scientists in eutrophication research:

> "Eutrophication – in its most generic definition, that applies to both fresh and marine waters – is the process of enrichment of waters with plant nutrients, primarily nitrogen and phosphorus, that stimulates aquatic primary production and in its most serious manifestations leads to visible algal blooms, algal scum, enhanced benthic algal froth and, at times, to massive growth of submersed and floating macrophytes."

During these ageing processes decaying organic material consumes and sometimes depletes the oxygen in the water causing a number of secondary problems such as fish kill, formation of undesirable substances such as methane, hydrogen

Outlook Box 9.1 — From local to world-wide problems

During a comparatively short period of time, a few decades, a huge number of both small and large fresh and marine water areas all over the world have been seriously affected by eutrophication, a result of increasing discharges of phosphorus and nitrogen from modern society.

Most countries would be represented in a list of eutrophied lakes and reservoirs of different size, from small ones to that of the huge Lake Victoria in Africa. Many estuaries and bays are found in the most intensively fertilized environments on Earth, e.g., those along the coastlines of North and South America, Africa, India, Southeast Asia, Australia, China, and Japan. Examples of eutrophied marine areas are: The Adriatic Sea, The Baltic Sea, The Black Sea, Cheasapeke Bay, The Seto Inland Sea in Japan, and The Gulf of Thailand. Most of these water bodies have a slow water exchange with the ocean, and are thus in a more difficult situation.

Marine eutrophication has became a large scale and world-wide problem in many coastal areas. Aquaculture, such as shrimp farming in Southeast Asia, is especially polluting. In Southeast Asia large stretches of the mangrove coastal forests have been removed to allow shrimp farming, which enhances eutrophication. Tourism is another important factor for eutrophication of coastal areas, especially when there are not proper measures to manage sewage from hotels, etc.

Figure 9.12. Algal bloom. The girl is entirely surrounded by the green algae floating on the surface of the eutrophied water. Swimming is less pleasant in such conditions and some algae are even toxic to man and animals. (Photo: André Maslennikov.)

Eutrophication

"Eutrophication – in its most generic definition, that applies to both fresh and marine waters – is the process of enrichment of waters with plant nutrients, primarily nitrogen and phosphorus, that stimulates aquatic primary production and in its most serious manifestations leads to visible algal blooms, algal scum, enhanced benthic algal froth and, at times, to massive growth of submersed and floating macrophytes" (Vollenweider, 1992).

Eutrophication is equally important for terrestrial environments. Addition of nutrients to a land area will cause plants favoured by higher nutrients to have an advantage and outcompete those which are favoured by poorer soils. Ammonia will also be oxidised to nitrous or nitric acid and then cause acidification.

Main problems associated with aquatic eutrophication

A. Water quality impairment (freshwater)

- bad taste, odour, and colour; difficulties to conduct filtration, flocculation, and sedimentation,
- oxygen depletion; pH changes, increased concentrations of Fe, Mn, CH_4, and H_2S
- toxicity

B. Recreational impairment (fresh and marine waters)

- anaesthetic water, increased turbidity
- hazard to swimmers
- increased health hazards

C. Fisheries impairment (fresh and marine waters)

- fish mortality
- undesirable fish stocks

sulphide, ammonia, taste and odour producing substances, organic acids, and toxins. When accumulating in fish, particularly shellfish, toxins from algae may be a threat to human health. In freshwater toxins from cyanobacteria can cause livestock mortality.

It is primarily the biological effects of increased nutrient inputs that leads to visible changes and problems. These effects are here included in the concept of eutrophication, though it should be kept in mind that there are two steps involved, namely increased input of nutrients and the biological effects of these nutrients.

Eutrophication is also a phenomenon equally important for terrestrial environments. Addition of nutrients to a land area will cause plants favoured by higher nutrients to have an advantage and out compete those which are favoured by poorer soils. Ammonia will also be oxidized to nitrous or nitric acid and then cause acidification. These effects are especially of considerable importance in forest ecosystems.

The understanding of eutrophication is based on physiological and ecological studies on aquatic plants. Cornerstones in the development were the studies during the 1940s on environmental requirements of freshwater plankton algae. During the 1950s, more attention was paid to primary production and development of algal biomass. More management oriented studies began to appear during the 1970s and 1980s with focus on the limiting nutrient concept.

Another cornerstone in the development of knowledge useful for water management was the concept of maximum permissible loads of nitrogen and phosphorus. Further limnological studies on eutrophication, conducted by the Organisation for Economic Co-operation and Development (OECD) in the 1970s, resulted in models for nutrient load – lake response relationships. This was the first quantitative presentation of relationships between nutrient load and lake water quality. The key role of phosphorus as a limiting nutrient in inland waters was also further confirmed by this OECD study.

Eutrophication in lakes and the marine environment

The general consequences of increased input of plant nutrients to a water body are:

- increased nutrient concentrations in the recipient water,
- increased primary production as increased phytoplankton biomass, and increased growth of filamentous algae, and
- subsequent physical, chemical, and biological changes, e.g., decreased light penetration, oxygen deficiency, and fish kill.

The possible consequences of eutrophication in lakes are outlined in Figure 9.13.

Oligotrophic, nutrient-poor, water contains small amounts of nutrients available to plants, especially of phosphorus. This results in low primary production, low biomass of phytoplankton, and high penetration of light. Submersed macrophytes can grow deep in the lake, and this environment favours the growth of salmonide fishes. The bottom sediment layer grows slowly.

Increased input of nutrients may rapidly change the environment in a lake. Some phytoplankton species can be stimulated and will start to grow rapidly, out competing most other species. By developing big algal biomass these species, often cyanobacteria, drastically reduce light penetration into the water. Under these conditions, there may be not enough light to support photosynthesis in deeper parts of the lake, which means that the former submersed meadows of macrophytes disappear. The composition of fish fauna may change – salmonides are substituted with whitefish, and the bottom sediment layer grows more quickly, due to increased sedimentation of organic material.

During the 1960s, it became obvious that man-made eutrophication was causing an increasing and undesirable degradation of water quality in lakes and reservoirs.

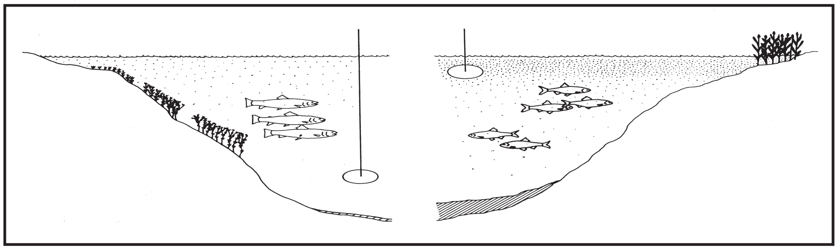


Figure 9.13. How water bodies change. *Oligotrophic*, nutrient-poor, water (left) contains small amounts of nutrients available to plants, especially of phosphorus. This results in low primary production, low biomass of phytoplankton, and high penetration of light. Submersed macrophytes can grow deep in a lake, and this environment favours the growth of salmonide fish. The bottom sediment layer grows slowly.

Eutrophic, nutrient-rich, water (right) has high primary production, high amounts of phytoplancton, and low penetration of light. The fish population changes, macrophytes grow less deep and muddy sediments build up. The circular dish represents a Secchi dish used for measuring light penetration.

The growing problem of toxic bacteria blooms of cyanobacteria has been of special concern. Interfering with beneficial uses of waters, this deterioration has also caused significant economic losses, which during the 1970s motivated the above-mentioned OECD comprehensive studies for increasing knowledge of how to control eutrophication. Since the mid-1970s, noxious and sometimes toxic algal blooms, anoxic conditions, and fish kills have been increasingly reported in marine areas.

Eutrophication may alter the recreational value of surface waters and impair activities such as fishing, swimming, etc. resulting in both social impacts and economic losses. In the Baltic Sea the massive increase of reed belts along the coasts and in shallow bays illustrates this. If marine eutrophication cannot be stopped, it may severely damage the production of fish and shellfish, with difficult consequences for society.

The main nutrients that can cause eutrophication are nitrogen and phosphorus. Other nutrients that can also influence the process of eutrophication are silica and many trace metals.

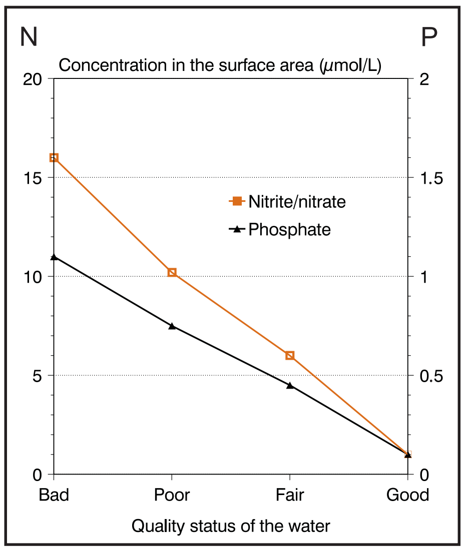
Nitrogen poisoning of wells

A common problem in many agricultural areas is nitrate leaking into wells. Leaching is more common in areas with sandy soils or in soils with generally higher permeability. Wells that are not deep are more exposed as are wells that are close to stables or areas where manure is stored. However, areas where eutrophication in general is a problem, e.g. caused by precipitation, may have a problem with high levels of nitrate in wells or in ground water.

Wells are mostly polluted with nitrate, the most oxidized form of nitrogen. Nitrate is quite harmless and is eaten in gram quantities in some therapies. Nitrite, however, is more poisonous. Nitrate is converted by certain bacteria to nitrite in the stomach, if the pH is not low enough. High nitrogen levels of nitrite in water has been implicated in several diseases. When nitrite leaks from the digestive system to blood it interferes with oxygen uptake. Nitrite is also considered to be cancerogenic. A highest level for nitrite in drinking water has been set within the EU to 50 mg per litre. This is lower than some national levels, e.g. the British one being 100 mg per litre. Wells with high levels of nitrate are also likely to be contaminated with bacteria, which also make the water less suitable for drinking.

It seems that nitrate in wells in most often connected to over-fertilization or bad management of manure piles. The remedy is thus to find a well at a more suitable place. Alternatively one may attempt to dig a much deeper well, which receives its water from deeper lying aquifers.

Figure 9.14. Water quality and P and N concentrations. As a rule of thumb, when P concentrations exceed about 0.5 µmole/litre and N about 5 µmole/litre the quality of water goes from good to poor. (EEA, 1998.)



Land eutrophication

A dramatically increased flow of nutrients is hitting not only water but also soil. The are several sources. *Atmospheric loading* of nutrients, especially of nitrogen, has increased remarkably since the 1950s, and today constitutes an important part of the total nitrogen load (Chapter 11). As mentioned above, man-made inputs of nitrogen to the atmosphere are caused by emissions of nitrogen oxides from combustion of fossil fuels in factories and power stations, combustion of fuel in transportation, combustion of biomass, and evaporation of ammonia from manure on farms. All land is reached by these increased amounts of nutrients. Below are some comments on the situation regarding agricultural land i.e. fields, forests, meadows, and parks.

Figure 9.15. Land eutrophication. The consequences of eutrophication on land can be considerable, e.g. flora can change and acidification increase. In some areas, such as in forests, growth first increases. (Photo: Lars Rydén.)

Fields systematically fertilized have a surplus of nutrients. Leakage from the fields to the surrounding land and water increases e.g. when the fields lay barren and when fertilizers are applied in periods when there is no growth.

Forests have traditionally been looked upon as being nearly closed ecosystems where nutrients are recycled with only a small amount of loss. Forest lakes are also normally oligotrophic. However, in recent years certain forest areas appear to have become "saturated" with nitrogen. Most importantly perhaps this is caused by the high atmospheric nitrogen deposition. But nutrients are often added to forests and other "cultivated" areas, such as parks and gardens. Forest fertilization is thus an important factor. Finally, modern forest management increase losses of nutrients through deforestation, construction of forest roads and ditching (channelization). These activities all increase microbial activities in the soil as air gets access. This in turn increases the mineralization, which releases nutrients bound to organic substances.

An immediate consequence of increased input of NO_x and in general nitrogen in forests is acidification. It seems that most forests accept a not too drastic soil acidification reasonably well (see further chapter 11). The lower the pH of the soil, the more serious it is for forest lakes which, especially at snow melt, get a boost of acidified drainage waster. The consequence of increased nitrogen in the soil is an increased production of biomass. Forest flora, traditionally consisting of plants adapted to nutrient poor conditions, are certainly impacted as well.

Meadows, traditionally used in agriculture for grazing animals, are today very often eutrophied basically through the same process as the forests. If the meadows are not harvested, as they were in the traditional agriculture, the biomass stays and a slow build-up of nutrients follows. Absence of grazing also contributes to build-up of nutrients. The result is a more or less drastic change in the ecology of the habitat. Meadows used to be the classical place to find a wide range of plants competing well on nutrient poor soils. In the new eutrophic situation faster growing grass gets an upper hand and meadows lose biodiversity and aesthetic value. To get out of this situation, meadows need to

Methods
Box 9.2

Determination of nutrient export

To estimate the amounts of nutrients exported to a water body, different methods are used for point and non-point sources. In general these require measurements at water courses or of deposition. Estimates can also be made in some instances by using known catchment area size, and coefficients for different land uses or population sizes.

Catchment areas: By determining both the nutrient concentration and water flow at a point in a water course, the total nutrient export from the upstream catchment can be calculated (concentration multiplied by flow). Both nutrient concentration and water flow may show great variation, and must therefore be assessed very frequently.

Treatment plants: A number of sewage treatment plants discharge directly into recipient waters. Here the export of nutrients is also determined by multiplying concentration by flow.

Direct sewage discharge into recipient waters: If no sewage treatment plants exist, the nutrient export from urban areas can be calculated by using estimated export coefficients. These coefficients may differ from country to country, depending on food intake pattern, use of household chemicals, and so on. For phosphorus the export may be 2-3 g per person and day. National figures must be estimated to reflect the actual situation. These figures may also change suddenly, e.g., when use of phosphorus-containing detergents is reduced.

Agricultural and forest areas: These areas represent non-point sources, and when not included in export estimations for whole catchments, the exports must be calculated by using areal coefficients (kg per ha and year). These figures must be estimated for different regions. Because there may be great variation in leakage of nutrients from soil to surface water, depending on variation in precipitation and groundwater level, among other things, these figures may be less accurate than direct measurements of concentration and flow.

Atmospheric deposition: The atmospheric contribution must be determined as both wet and dry depositions, which together constitute the total deposition of an element. An accurate determination of the export from this source may be complicated to estimate, e.g., for nitrogen, which occurs in different forms such as nitrate and ammonium.

Methods
Box 9.3

Measuring limiting nutrients

Several different methods are used to estimate the most limiting nutrient:

Nutrient supply ratios. By comparing the external input ratios of nitrogen to phosphorus, and these ratios in surface waters with the corresponding ratio of these elements in algal cells (16:1, as was mentioned earlier), an indication of the most limiting nutrient may be obtained. A ratio much below 16:1 indicates that nitrogen is limiting, while a ratio much above points out phosphorus as the key element. Input ratios, however, may be misleading since the amounts of nutrients in water available to plants may be drastically changed due to biochemical processes. This is the case in the Baltic Sea.

Nutrient enrichment tests. Addition of extra nutrients to algal cultures or natural plankton communities may demonstrate which nutrient momentarily limits further algal growth.

Quantitative determination of alkaline phosphatases. These enzymes split off phosphate from organic phosphorus compounds. Their presence may demonstrate that phosphorus is a limiting nutrient.

A combination of these approaches will give the most valid information.

be harvested as they were in earlier times, and the land has to be kept open. Animals serve an important function (see also Chapters 3 and 7).

Parks and lawns in gardens in urban areas go through the same process. In addition to nutrient input through deposition, fertilization is common. It is not difficult to see how the biology changes. For example the numbers of dandelion (*Taraxacum vulgare*) have increased dramatically since it competes well on nutrient rich soils.

The physiological basis for eutrophication – limiting nutrients

Eutrophication occurs when plants, or in general autotrophs, in presence of a surplus of nutrients grow and reproduce through photosynthesis, in which they produce organic compounds from carbon dioxide and water.

Algae and other green plants consist mainly of carbon, hydrogen, and oxygen (often more than 98% of the fresh weight). The sources of these elements are, as mentioned, carbon dioxide and water. In addition to these basic building blocks in production of organic matter, several other elements or nutrients are also necessary in larger amounts such as some metals – calcium, magnesium, potassium – the metalloid silicon, and the non-metals sulphur, nitrogen, and phosphorus. These are often called *macro-nutrients*. Other elements, needed in only very small amounts, are the trace metals, principally copper, iron, and zinc, as well as the non-metals boron, manganese, and selenium, and these are therefore called *micro-nutrients* or trace elements.

A shortage of an essential nutrient will limit plant growth. In aquatic environments nitrogen and/or phosphorus are the elements which most often play the key roles as limiting nutrients. Nitrogen is an important element in cellular proteins, and phosphorus has a key position in cell energy transfer. Both elements are needed in varying proportions depending on the specific requirements among different plant species. In phytoplankton organic matter, there are on average 16 nitrogen atoms for one phosphorus atom (16 N : 1 P). This ratio of nitrogen to phosphorus, called the *Redfield value*, roughly describes the algal consumption pattern of these elements. An indication of the most limiting nutrient may be obtained by comparing this ratio with the corresponding ratio between nitrogen and phosphorus concentrations in surface waters.

Shortage of a nutrient may limit primary production in three ways:

- the growth rate of an individual algal population,
- net primary production or net biomass accumulation, and
- net production of the ecosystem.

Redfield ratio

In phytoplankton organic matter, there are on average 16 nitrogen atoms for one phosphorus atom (16 N : 1 P). This ratio of nitrogen to phosphorus, called the *Redfield value*, roughly describes the algal consumption pattern of these elements. An indication of the most limiting nutrient may be obtained by comparing this ratio with the corresponding ratio between nitrogen and phosphorus concentrations in surface waters.

Limitation of net primary production or net biomass accumulation is the concept most often applied to nutrient limitation in aquatic ecosystems. Knowledge of which nutrient is most limiting for algal growth is of central importance for water management.

Eutrophication of the Baltic Sea

Nutrient loading

It is often stated that during the 1900s there has been a fourfold increase in the load of N, and an eight-fold increase in the load of P (Larsson et al., 1985) to the Baltic Sea. Most of the increase has likely occurred since 1950. Although there are indications that such an increase may have occurred, it must be kept in mind that quantitative estimates of long-term changes in the loading of nutrients are uncertain. During 1970-1993 the total annual riverine loads of N and P discharged into the Baltic Sea were fairly constant, with inter-annual variation correlated to freshwater runoff.

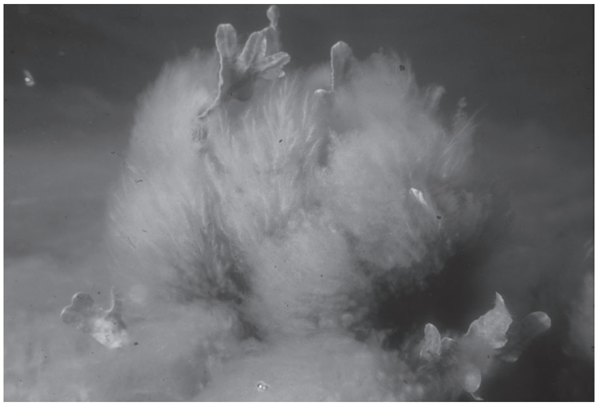
The input of nutrients to the Baltic Sea occurs along four pathways, namely through riverine runoff, direct emissions from industries and urban areas on the coast, atmospheric deposition on the sea surface, and through N_2-fixation.

Seepage of groundwater is also a possible way by which nutrients can enter the sea, but this input is regarded as playing a small role for the flux of N and negligible in the transport of P. Fish farms may locally be of importance, e.g. in the archipelago of Finland. There may also be some other minor inputs, e.g. from ships.

The riverine runoff of N and P exceeds in size those of direct discharges, atmospheric deposition, and N_2-fixation. During the period 1980-1993, the average annual river transports of N and P to the Baltic Sea were estimated to be 830,000 and 41,000 tonnes, respectively. The six largest river basins, namely the Neva, Narva, Daugava, Neman, Vistula, and Oder River Basins contributed with about 50% of the load of both Tot-N and Tot-P (see Table 9.2. Stålnacke, 1996).

Direct emissions into the sea from about 20 million people living in areas along the coast of the Baltic Sea amounts to a substantial volume of nutrients. Estimated coastal point-source pollution of nutrients are about 95,000 tonnes per year of N and 12,500 tonnes per year P. The industrial discharge of P direct into the sea was estimated to be 10,000 tonnes per year (HELCOM, 1993).

Figure 9.16. Bladderwrack (Fucus) in eutrophied coastal water. In eutrophied water the bladderwrack, *Fucus vesiculosus*, is overgrown with filamentous algae and finally killed. (Photo: Katrin Österlund.)



Atmospheric deposition of N is primarily composed of nitrate from combustion of fossil fuels and exhaust from motor vehicles, and ammonium from agriculture, particularly from livestock farming. The origin of P in this context is less important, although combustion of organic matter, sea-spray, and wind erosion of soils have been suggested to be the dominating sources. The nitrogen atmospheric deposition to the Baltic Sea increased during the 20th century and was about 330,000 tonnes per year in the middle of the 1980s. Since then it decreased to about 250,000 tonnes per year in the middle of 1990s. The decrease is caused both by reductions of nitrogen emissions and by favourable weather conditions during recent years. There is a clear gradient between different basins: from 1,000 mg N/m^2·yr in the southern Baltic to less than 200 mg N/m^2·yr in the Bothnian Bay (HELCOM, 1997). For P several investigations propose a range of 5,500-6,000 tonnes per year.

N_2-fixation by blue-green algae, properly called cyanobacteria, where nitrogen gas is transformed into bioavailable N, has been estimated to contribute

180,000 to 430,000 tonnes per year to the Baltic Sea proper (Larsson et al., 2001). In other sub basins N_2-fixation is regarded as insignificant.

Total inputs of nutrients. In spite of refinement of data treatment there is no consensus regarding the total nutrient loads on the Baltic Sea. Recent data for riverine loads of nutrients are higher than some of those previously presented but also show good agreement with other estimates for the river transport of nutrients. The discrepancies could be explained by earlier scarcity of information about nutrient concentrations and uncertainties in data treatment. The total input of nutrients along the four major pathways listed above is here documented with data from a comprehensive and recent study (Table 9.2). The dominating role of riverine transport of N and P is very evident, and corresponds to about 60%. A substantial contribution of the N load comes also with atmospheric deposition and nitrogen fixation, about 30%. It should be noted that the riverine load from the catchment areas also includes atmospheric N, deposited on the actual land area.

Are N or P limiting nutrients?

The external loading of nitrogen and phosphorus to all subareas of the Baltic Sea generally has a ratio greater than 16:1 (Table 9.2). The ratio between these elements in winter surface waters is variable (Figure 9.17). In the Bothnian Bay, the ratios are higher than those of the input loads, while in the Baltic proper and the Kattegat, the ratios are relatively lower. These differences may reflect the importance of internal processes which can regulate nutrient

	Runoff (10^9 m^3/yr^1)	NO_3-N (tonnes/yr)	total-N (tonnes/yr)	PO_4-P (tonnes/yr)	total-P (tonnes/yr)
Gulf of Bothnia					
Kemijoki	18.9	1,100	6,900	140	420
Lule R.	16.7	560	3,300	40	180
Ångermanälven R.	17.1	890	4,650	35	200
Indalsälven R.	15.3	1,390	4,540	25	140
Other monitored rivers	11.5	15,980	60,250	1,020	3,250
Non-monitored rivers	24.3	7,960	20,750	610	1,220
Subtotal	103.8	27,880	100,390	1,870	5,400
Gulf of Finland					
Neva R.	81.7	21,260	55,590	1,200	3,210
Narva R.	14.3	4,010	26,400	290	750
Other monitored rivers	18.5	11,830	17,110	550	660
Non-monitored rivers	7.7	8,620	26,870	560	1,510
Subtotal	122.2	45,720	125,970	2,600	6,130
Gulf of Riga					
Daugava R.	23.3	28,680	70,130	970	1,330
Other monitored rivers	9.7	21,480	35,940	450	670
Non-monitored rivers	3.3	4,120	7,160	90	240
Subtotal	36.3	54,280	113,230	1,510	2,240
Baltic proper[1]					
Neman R.	20.5	31,650	58,340[1]	4,140	5,410
Vistula R.	32.4	59,280	119,080	3,570	5,510
Oder R.	16.3	41,900	71,430	2,510	6,630
Other monitored rivers	19.9	18,760	36,430	900	1,340
Non-monitored rivers	23.9	41,410	77,740	2,100	4,300
Subtotal	113.0	193,000	363,020	13,220	23,190
Western Baltic[2]					
Göta R.	18.0	10,080	16,250	60	300
Other monitored rivers	11.4	47,620	57,210	880	1,860
Non-monitored rivers	8.0	38,980	49,830	1,110	2,040
Subtotal	37.4	96,680	123,290	2,050	4,200
Total Baltic Sea	412.7	417,560	825,900	21,250	41,160

[1] Excluding the Gulf of Bothnia, the Gulf of Finland and the Gulf of Riga
[2] Including the Kattegat

Table 9.2. Time-averaged runoff and riverine export of NO_3-N, total-N, PO_4-P and total-P to the major sub-basins of the Baltic Sea, 1980-93. The selected rivers are the eleven largest in the Baltic Sea drainage basin. (Source: Stålnacke, 1996.)

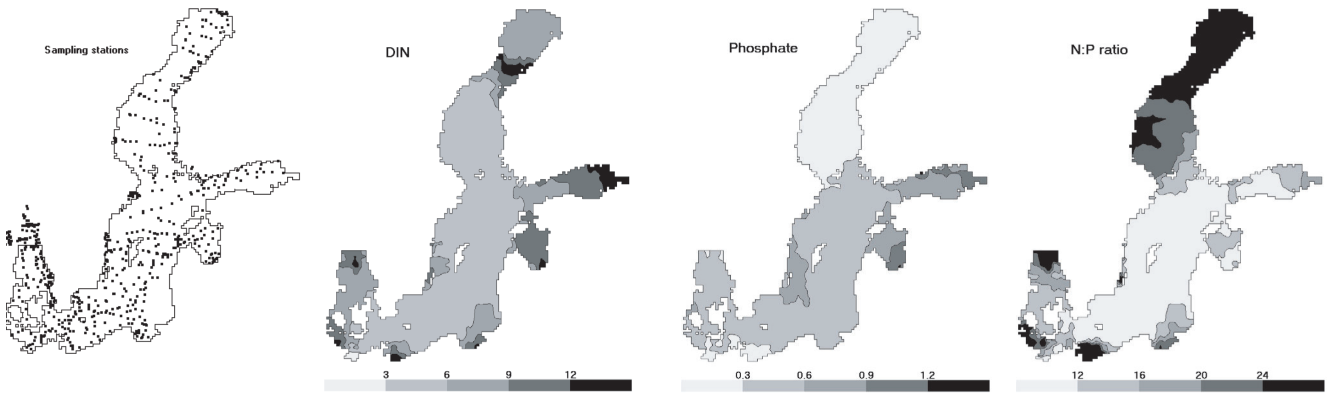


Figure 9.17. Monitoring the Baltic Sea. There are a large number of sampling stations in the Baltic Sea. Various parameters are measured regularely. Monitoring stations are shown on the maps, as well as surface distributions for dissolved inorganic nitrogen (DIN), phosphate:nitrogen ratio, and phosphate. It is clear that growth of biomass is limited by different factors in different basins, for example the Bothnian Sea is phosphate limited, while the Baltic Sea proper is nitrogen limited. (Data from Baltic Environment database, BED)

concentrations, for example through a regeneration of nutrients from organic matter in surface waters, or benthic denitrification in shallow waters or in nearly anoxic deep waters, or low solubility and precipitation causing sedimentation.

Nutrient enrichment tests generally indicate nitrogen limitation in the Baltic Sea proper and the Kattegat, although algal growth was stimulated by phosphorus addition in the Baltic Sea proper during summer blooms of blue-green algae. Nitrogen may also be the most limiting nutrient in coastal areas of the Baltic Sea proper which are not directly influenced by nutrient inputs. Large-scale denitrification in the sediments is the explanation for low nitrogen to phosphorus ratios in the Baltic Sea proper.

In the Bothnian Bay, phosphorus plays the key role as a limiting nutrient (Figure 9.17). High ratios of nitrogen to phosphorus may be explained by couplings of phosphate to iron in forest river waters discharging into this bay. Low solubility and precipitation may cause sedimentation of phosphorus. Primary production will be low which means that only small proportions of inorganic nitrogen is bound in organic matter settling to the bottom.

Biological consequences of eutrophication

Because most of the nutrient load is derived from land, the nutrient concentrations in coastal waters are usually higher than in the open sea. Consequently, the biological changes due to eutrophication are often more pronounced in coastal zones than in large, open water areas. For example, it has been difficult to demonstrate statistically significant biological effects of eutrophication in the open Baltic Sea. The reason for this may be lack of an adequate monitoring program rather than that there are no such effects at all.

As shown by many case studies all around the Baltic Sea, the changes in the coastal waters are numerous and differ from location to location. Generally, the diverse biotic response can be summarized as follows (Cederwall and Elmgren, 1990, cf. also Figure 9.18):

- increased primary production,
- increased algal blooms,
- increased chlorophyll a concentrations,
- increased deposition of organic matter on the bottom,
- increased macrobenthic biomass ,
- increased frequency and severity of oxygen deficiency in bottom waters,
- decreased water transparency, and
- decreased depth penetration of *Fucus vesiculosus.*

An idea of the magnitude of long-term changes in the entire Baltic Sea ecosystem can be obtained from estimated changes in major energy flows expressed as organic carbon. The following data illustrate human impact in the 20th century (Elmgren, 1989):

Diatoms are mostly unicellular microscopic algae (*Bacillariophyta*). Their cell wall is built on silica. One of their characteristics is that their cell wall is doubled, overlapping each other. Si:DIN refers to the ratio of silica concentration to the number of diatoms.

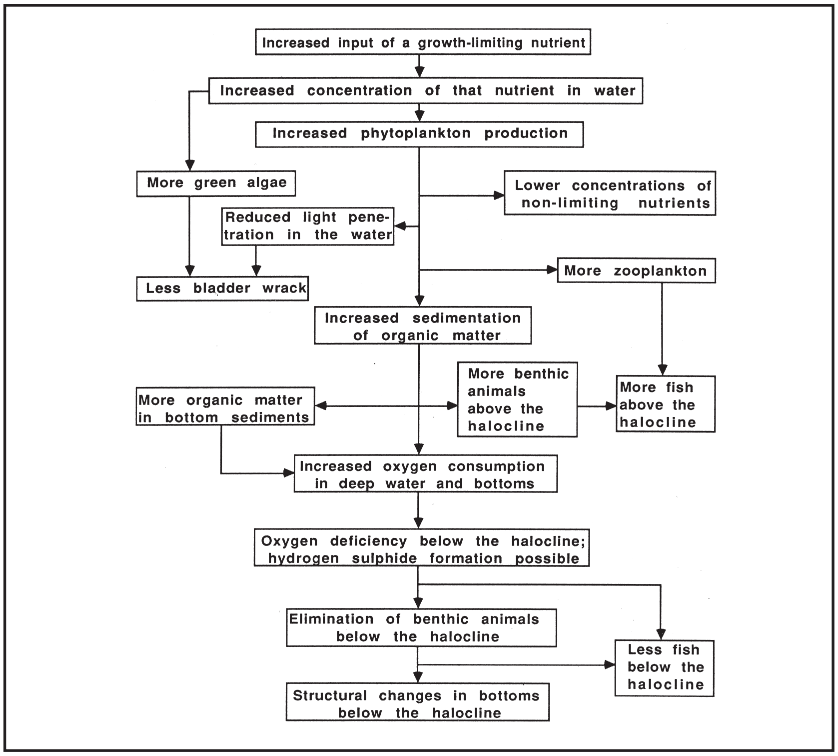


Figure 9.18. Consequences of eutrophication in marine environments. Eutrophication especially causes the growth of algae and higher organisms. (Modified from Monitor, 1988)

- increased pelagic primary production by 30-70%,
- increased zooplankton production by 25%,
- increased sedimentation of organic carbon by 70-190%,
- an approximate doubling of the macrobenthic production above the halocline
- more than tenfold increase in fish catches (partly due to doubled fish production, but more to increasing fishing effort).

Algal blooms and nitrogen fixation

The most striking aspect of eutrophication may be the phytoplankton blooms, when mass development of microscopic algae over large water areas drastically reduces transparency and sometimes also creates surface scum and odours. Some such blooms, created by so called harmful algae, may be toxic for marine organisms and poisonous to people.

In the Kattegat and other more saline parts of the Baltic Sea area, several dramatic blooms of toxic species have occurred during recent decades: *Prorocentrum ssp.*, and *Dinophysis* among the dinoflagellates, *Dichtyocha* among the chrysophyceans, and *Prymnesium* and *Chrysochromulina* among the prymnesiophyceans. Some of the recent blooms have killed pelagic organisms as well as the bottom fauna and flora. The best known bloom so far was the very extensive and severe bloom of *Chrysocromulina* in 1988 along the Danish, Swedish, and Norwegian coasts reaching as far north as Bergen in Norway (Figure 9.19).

However, the most common feature of the Baltic Sea is the blooms of blue-green algae that have been reported since the middle of the 19th century. Studies in the late 1800s and early 1900s demonstrated mass occurrence of the blue-greens *Nodularia spumigena* and *Aphanizomenon flos-aque*. Today the same cyanobacteria species form spectacular summer blooms, which extend over wide areas of the Baltic Sea proper (Figure 9.20).

These blooms may be harmful as well. *Nodularia* produces a peptide (a chemical compound consisting of amino-acids) called hepatoxin, which can degenerate liver cells, promote tumours, and cause death from hepatic haemorrhage. Toxic events and poisoning caused by blue-green algae in the

Figure 9.19. The *Chrysochromulina* bloom in 1988. The figures indicate the density of *Chrysochromulina polylepis* (million cells per litre) during the bloom in 1988. The dates, from 8 May (mai) to 3 June (juni), show how the algae migrated north along the Swedish and Norwegian coasts. (Modified from Berge and Dahl, 1988.)

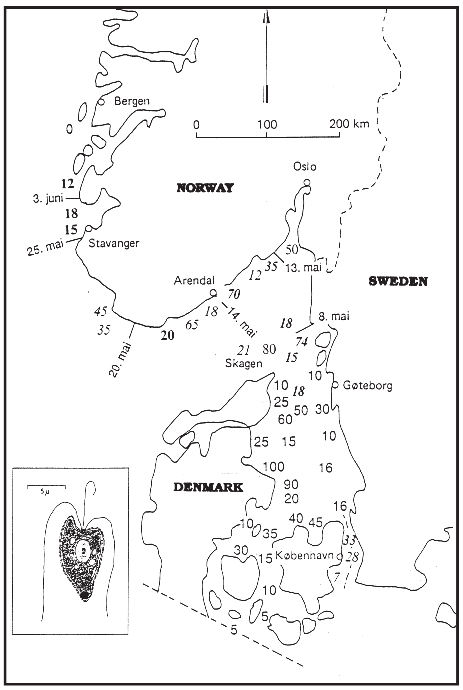
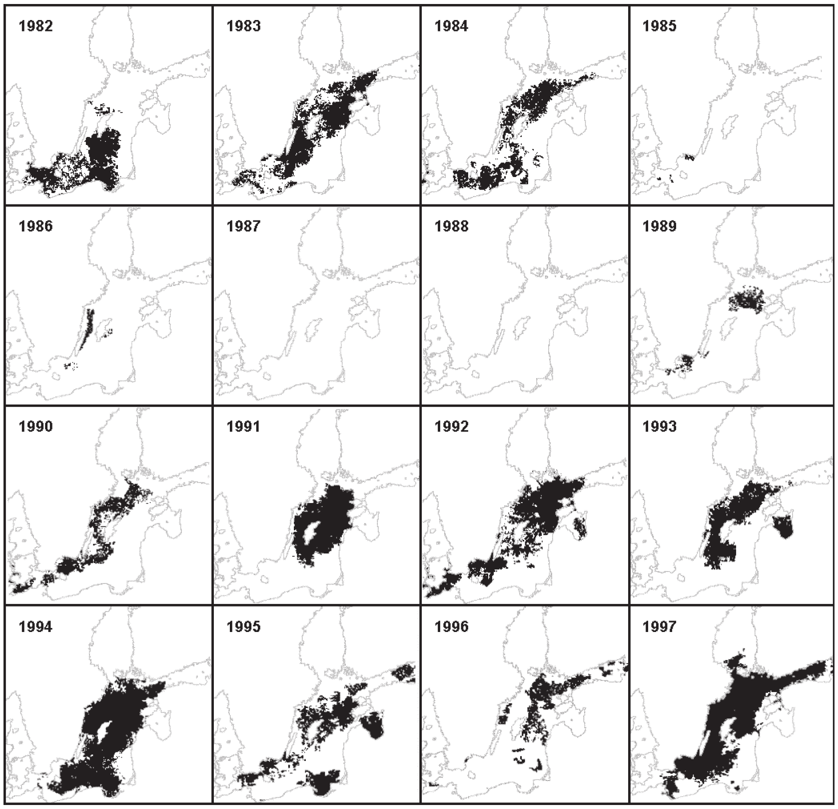
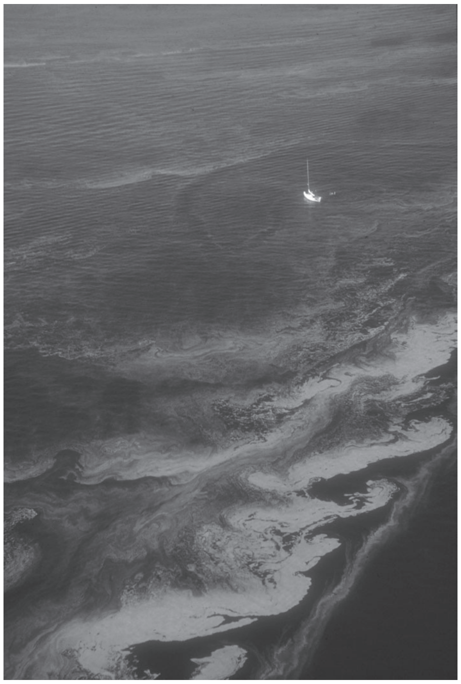


Figure 9.20. Surface accumulations of the blue-green algae (cyanobacteria) in the Baltic Sea, July-August 1982-1997. (Modified from Kahru, 1997)



Baltic Sea have been reported since the beginning of the 1960s. In addition to ducks, cattle, and dogs dying from intoxication, there are also reports that people swimming in the sea during blue-green blooms have suffered from stomach complaints, headaches, eczema and inflammation of the eyes. In some years, there has also been prohibition of swimming along certain shores where blue-green algae have accumulated (HELCOM, 1996).

Figure 9.21. Algal blooms occur regularely in the Baltic Sea. Recently the blooms have been larger and occur more often. (Photo: André Maselnnikov.)



In the eutrophication context, the most important is that both *N. spumigena* and *A. flos-aque* are able to fix molecular nitrogen (N_2) dissolved in sea water, thus providing an additional external input of nitrogen to the sea with the atmosphere as a practically unlimited source. Biologically fixed nitrogen then enters marine biogeochemical cycle via such common pathways as mineralization of organic matter and feeding of zooplankton. In fact, the nitrogen fixing capability of the Baltic Sea ecosystem is a quite unique feature, since no data on planktonic nitrogen fixation were found in other estuaries or coastal seas all around the globe except for the Peel-Harvey estuary in Western Australia (Howarth et al., 1988).

Although the exact reasons of such distinction are still under debate, one of the prerequisites for nitrogen fixation in the Baltic Sea was found to be a low N:P ratio in the water when inorganic nitrogen concentration is close to zero but phosphate is still available. In such an environment the blue-greens gain a competitive advantage over other algae unable to fix molecular nitrogen and that are thus severely nitrogen-limited. The warm water is another important condition for these thermophilic blue-greens that start to grow only when the temperature exceeds 10 – 12°C. Both these conditions can probably explain why the blue-green blooms are confined to the summer months.

Bottom oxygen depletion

As shown by paleoenvironmental reconstructions, the redox alterations between oxygenated and reduced conditions have been occurring in the Gotland Deep at least during the past 400 years and can be considered as a quite natural

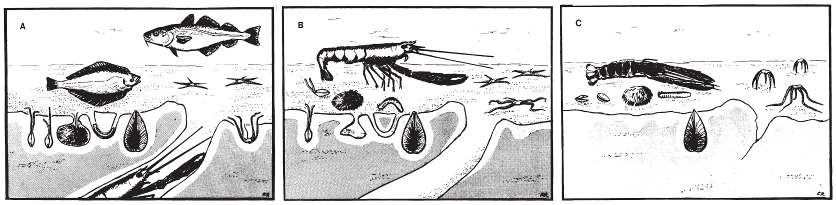


Figure 9.22. Bottom animals and oxygen. The drawings show the situation at the bottom of Kategatt. (A) Fish and the benthic macrofauna at normal oxygen levels. (B) At 15% oxygen saturation fish and large animals are gone. (C) At 5-10% saturation all higher life is gone. (After Baden et al., 1990.)

phenomenon. However, nowadays the anoxic conditions between major saltwater inflows might emerge sooner, cover larger areas, and last longer than earlier due to increased oxygen consumption. More direct indication of eutrophication is found in the coastal shallow waters where the natural seasonal minimum of oxygen concentration in July – October becomes deeper and the anoxic events occur more frequently and spread over larger areas (see further Chapter 5).

Oxygen depletion has devastating consequences for aquatic animals (Figure 9.22). At a dissolved oxygen concentration of about 2 ml dm^{-3}, fish migrate to areas with better oxygen supplies. Under hypoxic conditions (hypoxia, less than 2 ml dm^{-3}), problems arise for the benthic fauna, and many sensitive species die. When all free oxygen is used and is replaced by H_2S, hydrogen sulphide, higher organisms also die. When the toxic H_2S dominates the bottom layers, then all higher life cease to exist.

Eutrophication and fish populations

Total fish catches have increased tenfold in the Baltic Sea during the last 50 years. There are several explanations for this increase. The main reason might be improved technical fishing facilities, but other factors may also be important, such as the decreased number of seals that has reduced their preying on fish. The eutrophication has in general increased the productivity of the sea, including fish production.

However, eutrophication can also create negative environmental changes for fish populations. For example, cod (*Gadus morhua*) has its spawning habitat restricted to waters with salinity above 10 – 11 per mille (parts per thousand or Practical Salinity Unit, PSU) and oxygen concentration higher than 2 ml dm^{-3}, a combination found nowadays only in a few deep basins. Soon after the major inflow of salt water in 1994, the waters suitable for successful cod reproduction had occupied east of Bornholm island a volume of about 281 km^3, while two years later the volume was reduced down to 162 km^3 (Figure 9.23).

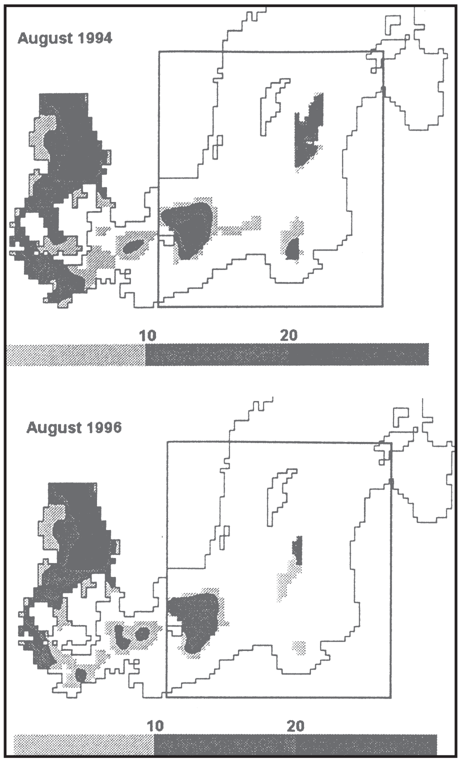
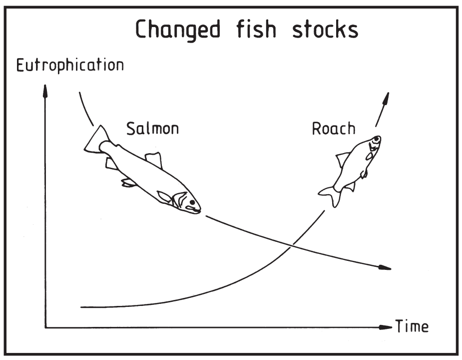


Figure 9.23. Conditions for cod reproduction. Cod reproduction requires oxygenated salt water. Cod-spawning habitat is shown as a thickness (meters) of the water layers with suitable conditions (Data from BED processed with the Data Assimilation System).

Herring (*Clupea harengus*) reproduces, in contrast to cod, along the coast, and spawns on littoral vegetation. Increased growth of filamentous brown algae may increase exudates from these algae that are toxic to herring eggs. Young herring feed mainly on zooplankton, while large herring to a large degree consume bottom-living organisms. This means that eutrophication may both stimulate and reduce herring growth; stimulation by increased zooplankton and shallow bottom fauna production, and reduction due to anoxic elimination of bottom fauna at some sites.

For freshwater species in eutrophied archipelagos, changes are similar to those in lakes. We find a decreased abundance of trout (*Salmo trutta*), whitefish (*Coregonus spp.*), burbot (*Lota lota*), ide (*Leuciscus idus*), and pike (*Esox lucius*). An increased abundance is found for roach (*Rutilus rutilus*), white bream (*Blicca bjoerkna*), and ruffe (*Gymnocephalus cernua*).

Figure 9.24. Eutrophication and fish stocks. With increasing eutrophication salmonide fish disappear and roach fish increase. (Forsberg, 1991.)



Monitoring and modelling nutrient flows

Monitoring and computer modelling of pollutants

Mathematical modelling, also called systems analysis, of pollution processes are becoming important tools in environmental science. The goals are to better identify and understand the process of pollution or environmental degradation, to predict future developments and identify the key measures needed to control pollution. The processes studied are often very complex and composed of a number of partial processes in complex interaction. A pollutant is described as distributed through a system of several subcompartments, where it undergoes various changes in each such subcompartement, to finally be degraded into harmless products or bound permanently.

The flows (fluxes) of a substance from each subcompartment to each of the others are described as a series of mathematical expression (differential equations), which are dependent on the concentrations in each of them, and a series of other factors such as temperature. The calculations are iterative, beginning with the chosen starting conditions and repeated at time intervals as the simulation proceeds. The result is depicted as a series of variables over time and space. Complex systems may require considerable computer power, which is, however, rapidly becoming available in many laboratories.

A very early example of a systems analysis was the “world model” published by the Club of Rome in the classic report, “The Limits to Growth” (1972). This analysis predicted a very bleak future for the world if pollution on the scale then seen would continue for about 100 years (Chapter 25). Today computer analysis of global warming due to increased atmospheric carbon dioxide may be the best known case of systems analysis (Chapter 10). It is of extreme importance since very far-reaching political decisions have been based on the results.

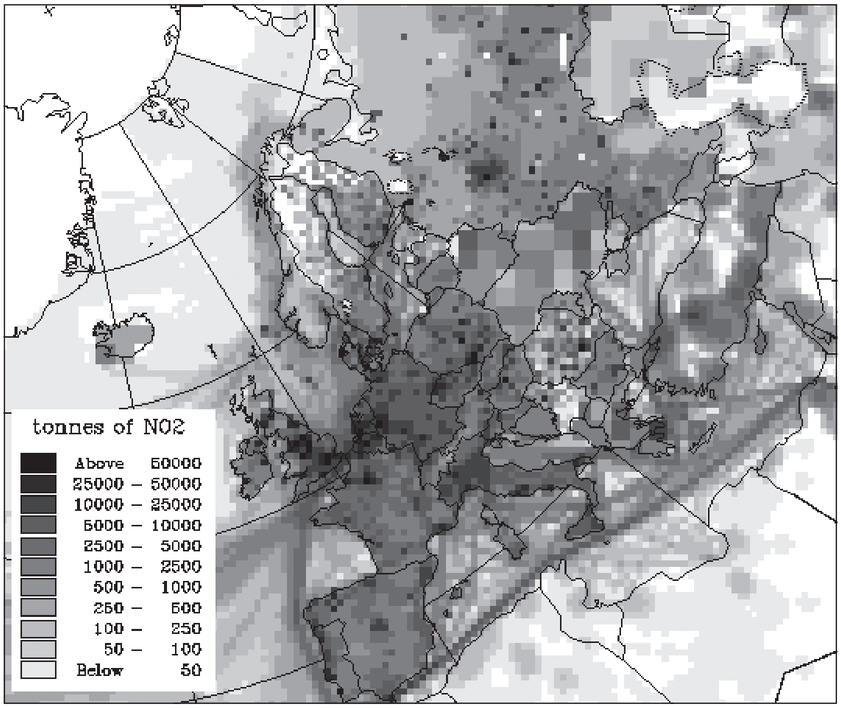


Figure 9.25. Emission of nitrogen oxides in Europe. The map shows the emissions of NO_2 in 1999 using the 50 km x 50 km EMEP grid. The largest emssions originate in continental Europe and are from power plants. Other major emission sources are agriculture (oxidised ammonia) and car traffic. (Source: EMEP, 1999. http://www.emep.int/emis_data/NOx_99.gif.)

Eutrophying pollutants in air are have been monitored for 20 years in a European cooperation based on the convention on long range trans-boundary pollutants. This cooperation has expanded to include more sophisticated modelling work to predict developments on which political decisions are based, e.g. on legal and economic measures for limiting pollutants. For the Baltic Sea region as a whole the United Nations Environmental Programme, UNEP, centre in Arendal Norway has established a programme to monitor the situation in the region. Data and results from all three activities are available on the GRID Arendal Website (www.grida.no). Some of the efforts are described below.

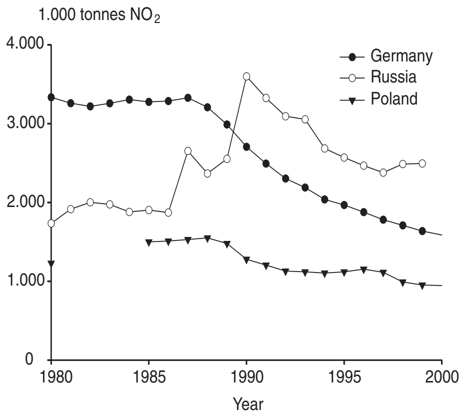


Figure 9.26. Anthropogenic emissions of nitrogen oxides (1980-1999, 2010) in the ECE region (1,000 tonnes NO_2 per year). NO_x emissions in Germany, Russia, and Poland between 1980-2000. (Source: EMEP, 2000. http://projects.dnmi.no/~emep/emis_tables/tab2.html.)

The European monitoring and modelling regime for air pollutants, EMEP

The Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe, called the EMEP programme, was established by European governments to regularly provide data required by the Convention on Long Range Transboundary Air Pollution (LRTAP) (Chapter 11). The EMEP programme relies on three main elements: (1) collection of emission data, (2) measurements of air and precipitation quality, and (3) modelling of atmospheric transport and deposition of air pollution.

The EMEP programme has since its start assessed eutrohying substances in air. The co-ordination and intercalibration of chemical air quality and precipitation measurements are carried out at the Chemical Coordinating Centre (CCC) in Moscow. The storage of data on emissions and the modelling assessment of sulphur and nitrogen pollutants is carried out by the Meteorological Synthesizing Centre - West (MSC-W) in Norway. In 1999 the Executive Body of the Convention decided to establish a Center for Integrated Assessment Modelling (CIAM) building on past modelling work, in particular the RAINS model.

The ECE emission database is based on the official national emissions reported through international programmes (e.g. CORINAIR, OECD, etc.), estimates of land-based emissions over regions within the EMEP modelling area, estimates of releases from international shipping, and estimates of biogenic emissions over the sea. The chemical components of concern include nitrogen oxides (NO_x = NO and NO_2) and ammonia (NH_3) on which estimation on eutrophying air pollution is based.

It is clear that eutrophying pollutants originate primarily from anthropogenic emissions of nitrogen oxides (NO_x) and ammonia (NH_3). Most of the NO_x is emitted to the atmosphere under the combustion of fossil fuel in electricity generating power stations, industrial plants, residential heating, and heating in the commercial and service sectors. Road transport, shipping, and aircraft are significant sources of NO_x emissions. NH_3 emissions are related to agricultural activities such as storage of manure, soil fertilising, animal husbandry, etc. When emitted to the atmosphere, acidifying and eutrophying pollutants may remain in air for several days and therefore, be dispersed and carried over long distances by winds. They can be transported across national boundaries and cause damaging effects far from the source of emission.

The amount of eutrophying pollutants in the air have not changed much for several years (Figure 9.26). They thus still accumulate in soil and water and the level of eutrophication increases slowly. The situation is more pronounced in the heavily industrialized and populated areas of the European continent.

EMEP

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Nutrient measurements in the Baltic Sea

The Baltic Sea is one of the best monitored waters in the world. A large amount of data has been collected within international and national monitoring programs, and scientific cruises. Many of these data, provided by all the major marine institutions around the Baltic Sea, are compiled into the Baltic Environmental

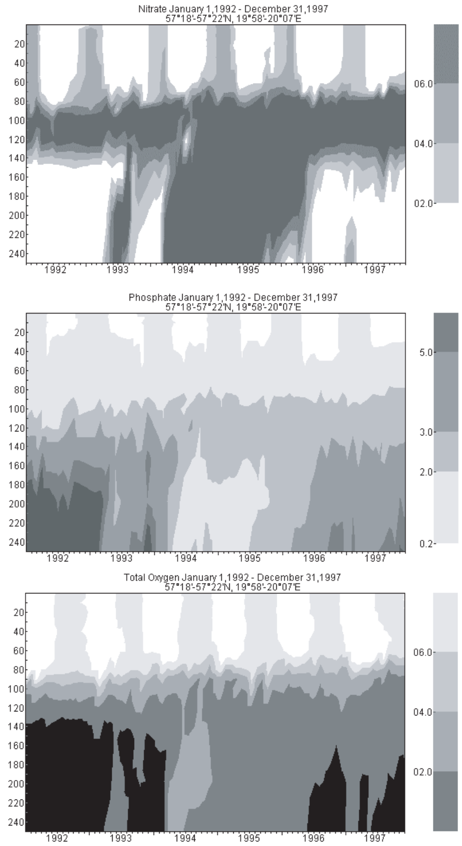
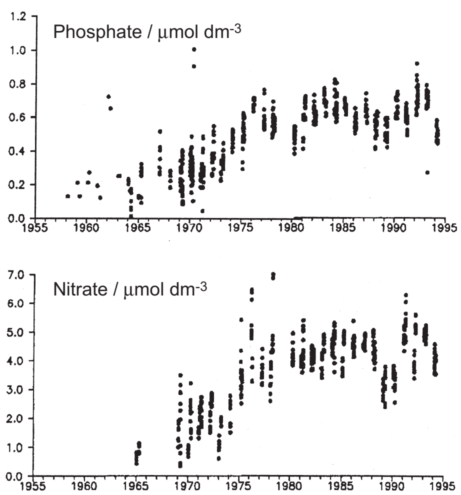


Figure 9.27. Interannual variations of nitrogen, phosphorus and oxygen. Monitoring data of bottom nutrient and oxygen concentrations at the Gotland deep over the period 1992-97 shows dramatic variation (Data from Baltic Environment database, BED).

Figure 9.28. Long-term trends in the Baltic Sea proper. The concentrations of nitrate and phosphate in winter surface water increased during the 1970s and leveled off during the 1980s (based on Matthäus, 1995).



Database (BED) at the Department of Systems Ecology, Stockholm University. With special tools for data analysis, data from BED were used to prepare the illustrations below (Sokolov et al., 1997).

Horizontal distribution: As shown above, the dominating source of N and P is the catchment areas with their riverine loads. Consequently, the nutrients generally show decreasing concentrations with increasing distance from the major rivers, and from inner parts of gulfs towards the open sea. Another large-scale feature is the opposite longitudinal gradients of inorganic nitrogen and phosphate concentrations that implies nitrogen limitation in the Baltic Sea proper and phosphorus limitation in the Bothnian Bay (Figure 9.17).

Seasonal dynamics: The nutrient concentrations in the upper water layers vary in relation to the production cycle and transports (Figure 9.27). The nutrient utilization during the spring algal bloom causes a fast reduction to low levels, while a developing thermocline slows down an upward transport from the deeper layers. In the summer time transient increases may occur due to heavy rain or upwelling of deep water. During the autumn and winter the algae production and biomass drastically decrease due to light limitation and enhanced vertical mixing, while the transport of nutrients from the deep layers increases because of thermal convection. The input exceeds uptake and nutrient concentrations continuously grow until the next spring. This results in a distinct winter maximum of concentrations that is considered as an indicator of the nutrient storage in the water body and, therefore, is used in the analysis of the inter-annual and long-term changes (Figure 9.28 and 9.29).

Due to the large longitudinal extension of the Baltic Sea this general scheme displays pronounced regional differences. In the Bothnian Bay the productive season starts in June and ends in September. In the southern Baltic Sea the productive season lasts from March to October.

Inter-annual variations: Seasonal dynamics of the upper water layers affects the deeper layers via biochemical destruction of sinking organic matter that releases nutrients and consumes oxygen. Here, in the dark deeps, the nutrient dynamics is opposite to that of sunlit surface layers: nutrients are accumulated during summer to be brought up by the winter thermal convection. This simple scheme holds for the Gulf of Bothnia where there is no sharp salinity stratification and inter-annual changes occur mainly due to weather variations (for instance, cold vs. warm years) and water exchange with the adjacent water basins.

The situation is quite different in the Baltic Sea proper where the permanent halocline impedes vertical exchange. The degree of stability of the halocline determines the flux and vertical distribution of nutrients. A halocline may be regarded as a "chemocline" as well, as it separates surface water with lower nutrient concentrations from nutrient enriched bottom water. Another important governing parameter here is the oxygen concentration.

Oxygen content in the surface layers is controlled by the exchange between sea and atmosphere, by the input from photosynthesis of green plants and by the consumption due to organism respiration. The only source of oxygen below the halocline is a transport caused by slow diffusion through the halocline and lateral transportation of oxygen-enriched waters due to sporadic saltwater inflows. The balance between "ventilation" and biochemical consumption defines the vertical distribution both of oxygen and, through redox conditions, of nutrients. Nitrate is removed from the bottom water at low oxygen concentration by denitrification, while phosphate during similar conditions is released from the sediments.

The described combination of transports and biogeochemical processes results in complex inter-annual variations (Figure 9.27). The long stagnation period of 1978 – 1993 (cf. Chapter 5) had stripped the deep layers of nitrate and enriched them with phosphate. The transport of oxygen with saltwater inflow in 1993 was comparatively small and anoxic conditions soon returned to be swept out again by the inflow of 1994. The oxygen concentration in the near bottom waters increased up to 3-4 ml dm^{-3}, such high values had not been measured there since the 1930s. However, the oxygen consumption nowadays is more intensive due to eutrophication and the hydrogen sulphide appeared again after two years. These alterations of redox conditions are clearly reflected in the opposite dynamics of nitrate and phosphate.

Long-term variations and trends. The winter surface concentrations of nitrate and phosphate increased in all sub-regions of the Baltic proper during the 1970s (Figure 9.28). Since then the nitrate concentrations have fluctuated at a high level, while the phosphate concentrations decreased significantly during the 1990s (Figure 9.29), mostly because of the drastic alterations of deep-water oxygen conditions (cf. Figure 9.27).

The increasing trends could also be noted for the concentration of both nitrogen and phosphorus in the Gulf of Bothnia with the exception of the Bothnian Bay, where phosphate concentrations has decreased. This increase could be to some extent explained by increased riverine loads as a consequence of higher river run-off during the 1980s compared to the 1970s (HELCOM, 1996).

In addition to nitrogen and phosphorus, silica is another important nutrient to be considered both as an indicator and as secondary driving force of the eutrophication in the Baltic Sea. A decrease in silicate concentration might reflect increased uptake by diatoms, which growth is stimulated by increased nitrogen and phosphorus concentrations. On the other hand, decreased silicate reserves can eventually become limiting for the diatoms, and as a consequence give rise to changes in phytoplankton species composition and food web dynamics. The silicate concentrations decreased significantly during the 1970s and the 1980s in all depths below the halocline in the Baltic proper, and also in the Kattegat, Kiel Bight, and Gulf of Bothnia (HELCOM, 1996). Significant long-term decrease in Si:DIN ratio in the surface layer that cannot be explained by a corresponding decrease in river input also implies that the Baltic Sea ecosystem approaches the state of silica-limited spring diatom blooms (Rahm et al., 1996).

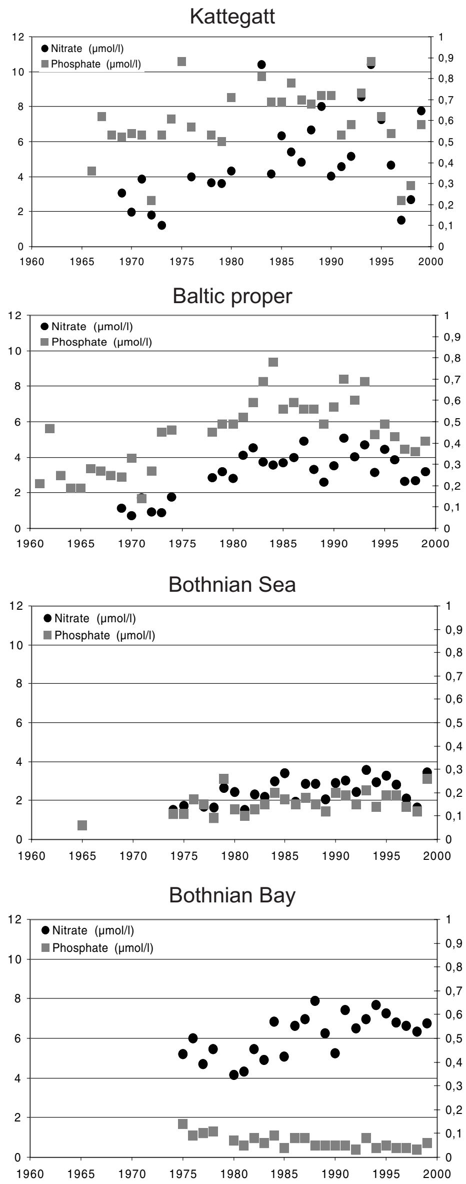


Figure 9.29. Winter surface nutrient concentrations in the four subbasins of the Baltic Sea. There is a decreasing trend in the Baltic proper since the mid-1990s. N-values are read from the left and P-values from the right scale. (Statistics Sweden, 2001).

Turnover of nitrogen and phosphorus in the Baltic Sea – the long term prediction

The turnover of nutrients in the Baltic Sea may be difficult to estimate accurately, especially for nitrogen, where both nitrogen fixation and denitrification contribute to the biogeochemical cycle. In principal, part of the total nutrient input settles to the bottom, bound in dead phytoplankton or other particulate matter. Due to denitrification, part of the nitrogen will return to the atmosphere, from which it may then be fixed and reintroduced into the marine ecosystem again. A certain amount is exported from the system via Kattegat to Skagerrak. The differences between inputs and outputs will cause either accumulation or reduction of total storage.

Nutrient budgets calculated with empirical models (Wulff and Stigebrandt, 1989; Wulff et al., 1990) show that about 90% of the total phosphorus load enters the Baltic proper, while less than 10% of this input is exported to Kattegat (Figure 9.33). Most of the P will be accumulated in the bottom sediments, from which a recycling back to the free water mass may occur. The ability to fix P differs between the different basins, with higher relative capacity in the Bothnian Bay than in the Baltic proper.

The export of nitrogen from the Baltic Sea to Kattegat is also comparatively small, as is the accumulation in the water mass. Most of the nitrogen "disappears" through denitrification, most effectively in the Baltic Sea proper. A smaller amount is accumulated in organic material in the

Methods
Box 9.4

Mathematical modelling of Baltic Sea eutrophication

Simulating eutrophication - model requirements

Eutrophication, or an accumulation of nutrients within an aquatic or land system can be considered a misbalance in biogeochemical nutrient cycles, such that more nutrients come into the system than leave it. In order to understand why it occurs in the Baltic Sea and to predict what could happen in the future, we must know:

- how and what amounts of nutrients enter the sea,
- how much is assimilated and recycled in the water column,
- how much is accumulated in the sediments or returned back into the water, and
- what are the losses due to internal sinks and by water exchange.

Examples of *empirical* models, i.e. models which are derived solely from the measurements, are the Baltic Sea regional empirical nutrient budgets. These combine, within a mass balance approach, both the knowledge of the Baltic Sea marine system, and the estimates of external exchanges and internal transports derived from available data (Figure 9.33). These budgets are excellent generalisation revealing important relationships. They may be less powerful in predicting situations that have not occurred in the past, and which therefore are not reflected in the data.

For such purposes semi-empirical or *simulation models* are more useful. These aim at a numerical reproduction of all the major physical, chemical, and biological processes that define nutrient biogeochemical fluxes and, consequently, the changes of concentrations and biomass. These models are theoretical in a sense that their basic mathematical expressions are derived from general concepts and theories such as the conservation law, the principles of hydrodynamics and chemical kinetics, the postulates of population dynamics, etc. However, the descriptions of concrete processes in these models are very often based on empirical laboratory and field data. Moreover, the application of such a generally formulated model to a certain aquatic system requires empirical information that is characteristic to this system: morphological parameters, nutrient inputs, weather variations, exchanges across the system's boundaries, biotic community structure, etc.

Construction of the mathematical model

The formulation of the model starts from a system description of the object that combines existing knowledge and available data and helps to convert often vague modelling goals into the well-defined objectives of simulations. The next step is a selection of model variables, which is mutually interrelated with the spatial and temporal scales of simulated phenomena. Since the model by definition is an abstract image of the real system, it must be as simple as possible and only as complex as necessary to achieve the objectives.

To study a long-term development of eutrophication in a well-mixed phosphorus-limited lake it would probably be enough to simulate such a lake as a homogeneous reactor where phosphorus is cycling between a few variables (phosphate – organic matter – primary producers), and correspondent fluxes are calculated on an annual basis. However, to be able to forecast a harmful algal bloom for a concrete location situated at an open coast it will be necessary to construct a three-dimensional ecosystem model describing interactions among dozens of variables with daily resolution. It also requires sufficient knowledge to parameterize all important processes as well as enough data to run the model.

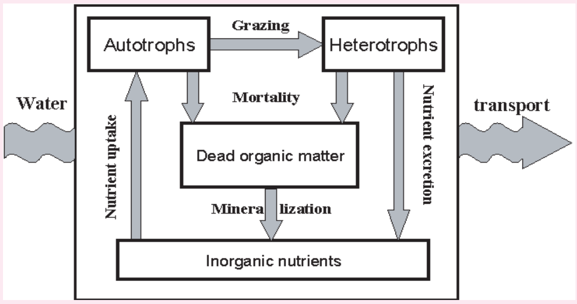


Figure 9.30. A simple model for nutrient turnover in the Baltic Sea. A model like this one is used in simulations of the development of eutrophication. (Source: Oleg Savchuk.)

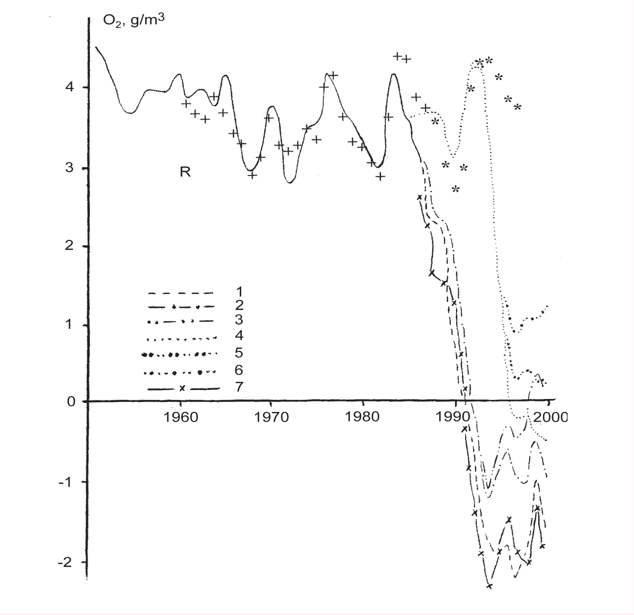


Figure 9.31. Comparison of measured with simulated data. Interannual variations of the average oxygen concentration below halocline in the Baltic Sea proper. The plot shows Fig.4 from Savchuk and Volkova, 1990 superimposed on observations: (+) – used for the model verification in 1990, (*) – extracted from BED in July 1998.

The next step is to translate a conceptual model like the one shown in Figure 9.30 into mathematical formulations. The basic principle here is a *mass balance approach* well known from the example of connected reservoirs – the water level (concentration in our case) in each of them is defined by the relation between inflows and outflows. In our example the dynamics of autotrophs and nutrients can be presented as follows:

change of biomass = uptake – grazing – mortality + influx – outflux
change of concentration = mineralization + excretion – uptake + influx – outflux

Parameterization

Next come parameterizations, describing how fluxes depend on model variables and other environmental factors. Among common principles used here are the first-order kinetics assuming that the flux is proportional to the amount (e.g. 10% of organic matter is mineralized daily) and the Lotka-Volterra interactions, where flux is proportional to both prey and predator biomass. The proportionality, in turn, can itself depend on concentration, and interactions become non-linear. For instance, the nutrient uptake is often defined as dependent on the water temperature, underwater light, phytoplankton biomass, and nutrient concentration.

The last but not least important step is to assign an initial distribution of variables and to supply the model with external forcing functions such as nutrient inputs, water exchanges, weather variations, etc. Sometimes it happens that "elegant" model formulations cannot be supported with available data and the model has to be reformulated accordingly.

Already fairly aggregated empirical (Wulff and Stigebrandt, 1989) and simulation (Savchuk, 1986; Stigebrand and Wulff, 1987) models have been useful to demonstrate that:

a) the eutrophication is driven mainly by increasing anthropogenic loads, while the natural changes cause only background year-to-year variations;
b) the adjustment of the system to changing inputs might takes several decades;
c) the decrease of inorganic N:P ratio in the water column will most likely stimulate nitrogen fixation.

However simplified these models are, they probably describe the most important large scale features of the Baltic Sea eutrophication and, consecutively, have some predictive power (Figure 9.31).

Developing the model

The experiences gained through experimentation with these models have led to the development of a biogeochemical model that simulates the coupled nitrogen and phosphorus cycles occurring in the pelagic and benthic systems at seasonal and long-term scales (Savchuk and Wulff ,1999).

To study large-scale long-term development of the eutrophication in the Baltic Sea proper this biogeochemical module has been coupled to a one-dimensional horizontally integrated hydrodynamic model with high vertical resolution. Such an approach has been developed earlier (Stigebrand and Wulff, 1987) and proved to be capable to simulate both the seasonal dynamics of surface layers and the inter-annual variations in deep layers.

To evaluate possible consequences of water management very drastic measures were assumed: a continuous reduction in land based nutrient sources during 20 years with a rate corresponding to 50% reduction every 5 years. This scheme (Figure 9.32) has been applied in three combinations: (A) nitrogen input reduced alone, (B) phosphorus input reduced alone, and (C) both N and P inputs reduced simultaneously. The prognostic simulations show that even with these drastic reductions the annual primary production would decrease with a moderate 20 - 30% in twenty years, at the best. The reduction of phosphorus was most effective, while only nitrogen reduction leads to a dramatic compensatory increase in nitrogen fixation.

The Gulf of Finland

The same biogeochemical model was also implemented in the Gulf of Finland, where the largest Baltic Sea region city St. Petersburg is situated at the mouth of the largest Baltic Sea region river, the Neva. Such a geographical situation creates sharp spatial gradients that required a spatially inhomogeneous approach: the whole gulf was divided into many homogeneous boxes and the water transport between them was simulated with a three-dimensional hydrodynamic model (Savchuk et al., 1997, Savchuk, 2000).

Even more dramatic reduction schemes were tested with the inputs from the St. Petersburg area “instantly” reduced by 50%. The effects in the eastern part of the Gulf of Finland were quite clearly seen already in two weeks due to short residence times (a few months compared to decades for the entire Baltic Sea). In the easternmost shallow area and in offshore waters the effect of nitrogen reduction far exceeded that of phosphorus, while for the so-called transient zone the phosphorus reduction was more important. Different reactions to reduction scenarios correspond to the gradient of limiting factors: in the shallow easternmost area primary production is light-limited by low transparency, while a strong phosphorus limitation in the transient zone is replaced with nitrogen limitation in the offshore waters.

These differences are also clearly reflected in the retention capacity of the region estimated from simulated biogeochemical fluxes. In August about 70 - 100% of the nitrogen input is retained and recycled in the Eastern Gulf. This area acts as a “phosphorus purification plant” since it imports phosphorus from the open Gulf in amounts equivalent to 60-160% of input from the St. Petersburg area. However, in November nitrogen retention is decreased to less that 5% of inputs, while external phosphorus inputs is further increased by an internal load from sediments. The simulations show that a reduction of phosphorus load simply will increase phosphorus import from the open Gulf and will not affect the nitrogen retention. The nitrogen load reduction converts this area into a nitrogen sink as well, even assimilating some nitrogen from the west. Thus, in contrast to the Baltic Sea proper, in the Eastern Gulf of Finland nitrogen load reduction seems to be more beneficial than that of phosphorus since it combines the local effects of reduced eutrophication with the long-range consequences of reduced load to the whole Gulf and the Baltic Sea.

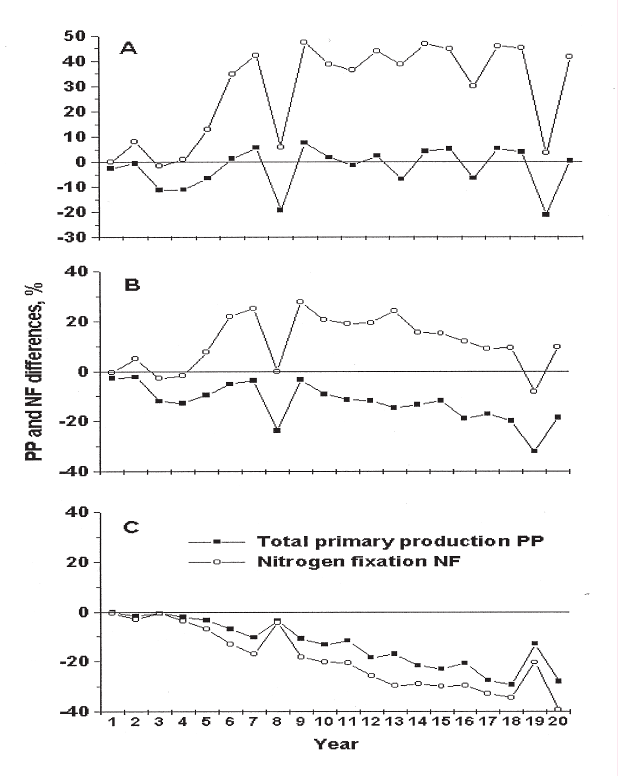


Figure 9.32. Predictions. The model is here used to predict the total primary production (PP) and nitrogen fixation (NF) over 20 years assuming drastic reductions of nutrient input from land. A) Nitrogen input is reduced alone. B) Phosporus input is reduced alone. C) Both nitrogen and phosphorus inputs are reduced. Thus even with an unrealistically fast reduction of nutrient inflow it takes 20 years to reduce primary production by 30%. (Source: Savchuk and Wulff, 1999).

Conclusions

Diagnoses and prognoses on the future development of the Baltic Sea, produced with these models, show that we have a fairly good understanding of the key processes controlling eutrophication in the Baltic Sea. But the simulations also demonstrate that by now the development of realistic scenarios for the future is most important for further model applications. Such scenarios have to take into account both climatic variations and socio-economic developments as well as complex interactions between them. This approach is an ultimate tool in a search for cost-effective solutions (Gren et al., 1987; Wulff et al., 2001).

Oleg Savchuk

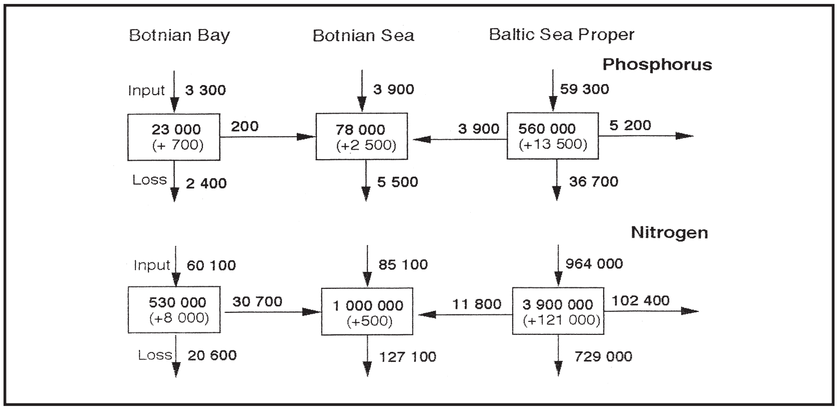


Figure 9.33. Average storage (tonnes) and annual change during 1971-1981 (tonnes yr^{-1}) are shown in the boxes. Net flows between subbasins, input from the catchment areas and the atmosphere, and internal sinks are indicated by arrows (tonnes yr^{-1}) (Modified from Wulff and Stigebrandt, 1989).

sediments. The loss due to denitrification is only in part compensated for by N_2-fixation.

The magnitudes of input data in Figure 9.33 differ somewhat from more recent estimates (see Table 9.2), but the differences may be considered negligible since uncertainties are always attached to this type of budget estimate.

Such budgets can also be used to estimate the so-called residence times of substances that show how fast the system will react to the changes in external impacts. Under the steady state assumption, the residence time is calculated as a total amount divided by the sum of in or out-flows of the system, thus indicating how much time the unit of substance would in average reside within the system. As these calculations show, the residence times of nitrogen (5 years) and phosphorus (13 years) in the Baltic Sea are much shorter than the residence time of salt (25 years) due to biogeochemical processes described above. They also imply that the system will not react immediately to changes in external loads and that the nitrogen is more labile than phosphorus due to denitrification.

The details of the nutrient fluxes for the Baltic Sea as a whole and for several of its sub-basins were studied using a systems analysis approach with long term simulations (see Box 9.3). It is clear that the nutrient status of the Baltic Sea will change only very slowly even if the load of nutrients are reduced drastically. We will certainly live with a eutrophic Baltic Sea for at least one to two generations, or even longer if nutrient outflows from society do not change dramatically.

Eutrophication in the future

Can large-scale marine eutrophication be stopped?

The development of large scale marine, as well as of fresh water, eutrophication is in principle regulated by:

- a growing population and urbanization in catchment areas,
- increased standards of living and food production,
- increased application of fertilizers (including manure), increased irrigation, and growing intensive animal production.

All of these give rise to substantial nutrient losses to soil, atmosphere, and water.

From agriculture there has been an increasing export of crops including nutrients to urban areas. These areas have expanded and are expected to continue to grow. More and more nutrients have been channelled through the food chain into the sewage systems, and have been discharged through pipes.

Growth has also occurred in the traffic sector where the emissions of N from cars substantially contributes to eutrophication.

A number of policy interventions, which aim to increase the efficiency of the use of these nutrients, have been introduced, where a combination of regulatory, advisory, and financial instruments is regarded as necessary to regulate agriculture efficiently (Tiessen, 1995).

In spite of the use of different policy instruments to reduce the flux of nutrients from land to water, it will be very difficult to stop large scale marine eutrophication. The reason for this is that a number of processes and mechanisms counteract the control measures taken so far. The following discussion, principally outlined in Figure 9.34, may illustrate the problems and the scale of the problems (taken from Forsberg, 1998).

Influence of population increase, urbanization and over-consumption

The world population is projected to double from the present roughly 6 billion to more than 12 billion within the next 50 years (Pimente et al., 1994). In order to feed a growing population, there is a need of an increased production of vegetative and animal food. For this purpose more fertilisers and more water for irrigation will be consumed. There is a significant relationship between the size of the world population and the consumption of raw phosphate. Based on existing agricultural practise an increase in food production will be difficult to manage without substantial losses of nutrients to water, especially in the absence of effective nutrient recycling systems.

A growing world population will produce increasing volumes of organic wastes, sewage, sludge, and ashes, and increasing emissions of N by combustion of N-containing fuels. There is a significant correlation between the population density in a watershed and export of nitrate and phosphate (Caraco, 1995) in the world's major rivers. These relationships clearly demonstrate a world-wide and central role of humans in the nutrient flux from land to water and ultimately to the sea. In general, increasing production and consumption of food will

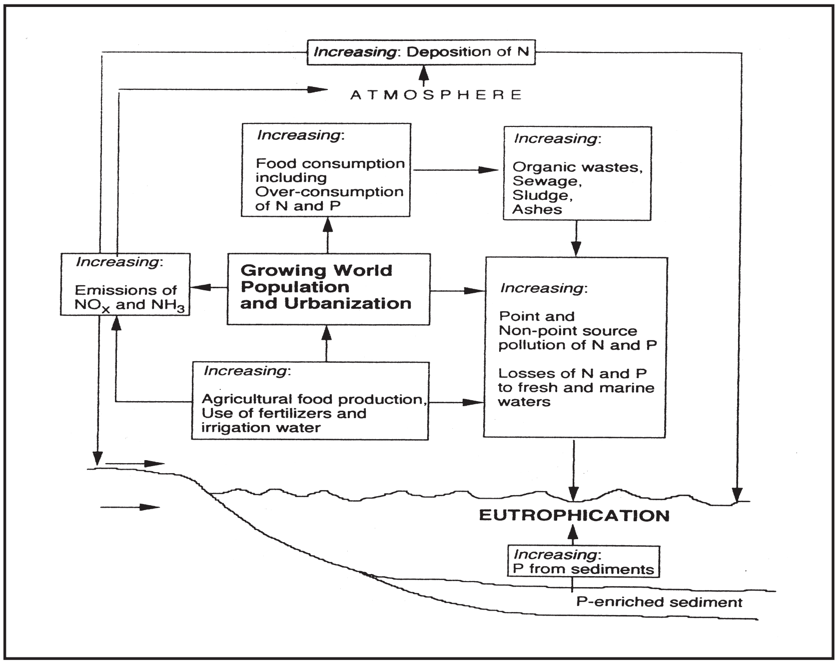


Figure 9.34. Growing world population and urbanization. The consequence is an increased flux of nutrients from land to water and increased eutrophication.

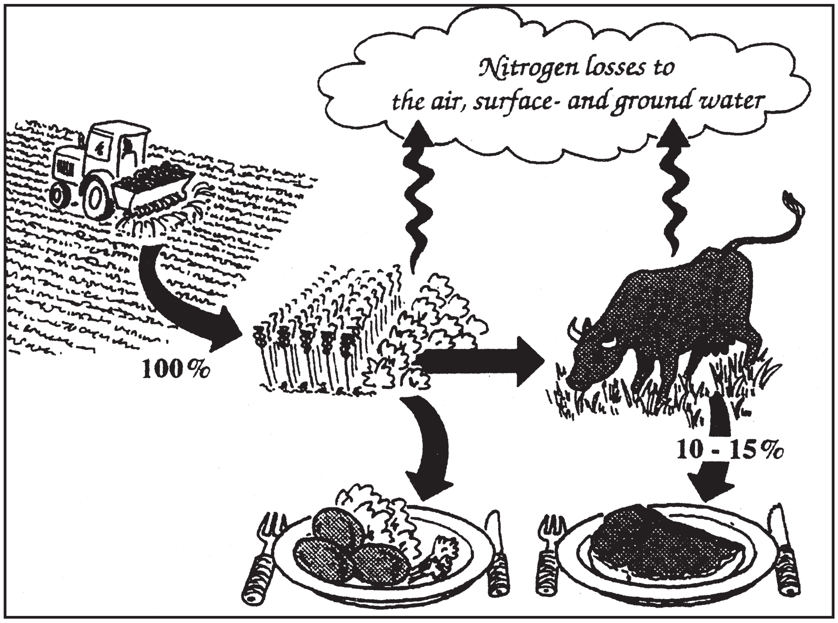


Figure 9.35. Nitrogen flows and food. Only 10-15% of the nitrogen which is needed in the production of meat ends up in the meat on our tables. (Modified from Forsberg, 1994a.)

result in an increase in both accumulations and losses of nutrients, from point and non-point sources, which may give rise to further eutrophication. It is apparent that the policies used so far to reduce nutrient fluxes to water, will not be sufficient to ensure a reduction in large scale eutrophication, unless the growth in the human population is curtailed.

The degree of urbanization is predicted to increase from 43% in 1960 to 60% in 2025 (Runge-Metzger, 1995), which means that more sewage will be channelled to water. Increased urbanization will also necessitate treatment of huge volumes of sewage, if it can be afforded. But as long as no effective recycling of nutrients between town and land has been developed, the nutrients in the growing volumes of sludge will be deposited, either directly or as ash after incineration. The size of future losses of P from sludge deposits is unknown.

In summary, increasing urbanization will directly result in increasing discharges of nutrients in sewage. It also makes recycling of nutrients more difficult (cf. Folke et al., 1997), which means that the deposited volumes of organic waste, sludge and ashes will increase. Urbanization will for a long time continue to support eutrophication, from both point and non-point source pollution.

The intensive, land independent animal production has in principle a structure similar to urban areas. There are too many organisms living on a small surface, where all are dependent on food produced on several times greater areas. Economical, technical, and practical barriers counteract recycling, with nutrient accumulations and increasing pollution of water as a consequence.

Figure 9.36. Ecological farming. Fertilizing the soil by growing legumes is used to increase nitrogen concentration and improving the soil. (Photo: Lars Rydén.)

Emissions of N to the atmosphere as N-oxides and ammonia can be a major N source from which direct and indirect (via drainage basin) deposition stimulate marine eutrophication. The biggest emissions of N-oxides comes from the transport sector, which will continue to pollute the Baltic Sea for a long time (Tengström, 1994). About 25% of all N which ends up in this water comes from the air. Emission of ammonia comes chiefly from agriculture, livestock farming, and storage and use of manure. At the EU level no directives exist on the subject of ammonia emission, and few technical options are available for reducing these emissions. Atmospheric N deposition will continue to stimulate marine eutrophication for a long time.

Losses of P from P-enriched sediments, so-called internal loading, will in many water systems contribute to future, long-term eutrophication of fresh and marine waters (see e.g., Cullen and Forsberg, 1988; Sas, 1989). Accumulation of P in closed marine environments may be very high, e.g., in the Baltic Sea. High internal P loading can be expected in the future, and with input of nitrate from surface and groundwater, of N by atmospheric deposition, and by N-fixing cyanobacteria, it is difficult to see which policies can stop or reduce this and the resulting large scale eutrophication in the reasonably near future.

The nutrients N and P are very central corner stones for structure and function of all living cells. Human beings consume N in proteins to cover the needs of amino acids. P is a key element in cell metabolism, with central functions in e.g., conversion of energy. Since N and P are parts of all plant and animal cells, our basic food-stuffs always contain these elements. Daily intakes are recommended in order to have certain margins of safety. However, in

Methods
Box 9.5

Sustainable nutrient management

To escape the trap of eutrophication a better nutrient management in society is required. The main components are indicated here. The goal is to stop linear nutrient flows.

Agriculture

Fertilisers are required in agriculture. Farms need to have both animal and crop production to balance nutrient flows. Manure is one of the most important nutrient sources for crop cultivation. A well working system for manure storage, handling and spreading is needed. The ammonia in the manure poses special problems. Technical systems to minimise losses are available.

Application of manure to fields has to be done with an acceptable precision in relation to the plant uptake of nutrients. The amount of applied manure per year should never exceed nutrients removed by crops. To prevent nutrient leakage, manure and mineral fertilizers may not be spread on frozen ground, nor applied to grassland before or after ploughing it up. To minimize nitrate leakage, at least 60% of land should be winter-grown. Leakage to water is also reduced by wetland areas and buffer zones.

Nutrients from slaughter of animals have to be managed properly. From 25-50% of the live weight of the slaughtered animals is of no use for human consumption. This should go back to farmland, e.g. using fermentation to produce biogas.

Household waste

Organic waste needs to be composted in the household or by the municipality.

The nutrient content in human wastes corresponds to a yearly production of 4-5 kg nitrogen and 1 kg phosphorus per capita. Urine may be used directly for fertilising fields.

The sludge collected in the mechanical step in the sewage plant could be reused on agricultural land after decomposition and dewatering. Inflow of heavy metals, toxic organics, etc., must be avoided. Fermentation is also possible.

Combustion

Combustion of fossil fuel or biomass in power plants, private furnaces, or in cars will produce nitrous oxides. Use of proper fuel, such as biogas or alcohol in cars, or proper treatments such as catalytic converters, minimise emissions of NO_x.

Ecological farming

A final sustainable nutrient management requires that some form of ecological farming is used. This contains three components:

A crop rotation scheme is normally more than four years. Its purpose is to reduce weeds as well as insect and pest infestations, to increase nutrient balance of the soil, to improve soil structure and to produce cereals for human food and fodder for animals.

Animals, mostly cattle or grazing animals, allow the fodder to be used efficiently. Cattle or sheep will use additional areas on a farm not suitable for crop cultivation. This will contribute to landscape and biological diversity. The proper and humane care of animals is also emphasized in ecological farming.

Nutrients are recirculated to the extent possible. Manure from animals is returned to the soil. Nutrient leakage from soil is reduced by proper cultivation of crops, including use of catch crops, a high degree of winter grown land etc. Tilling of soil is reduced as compared to conventional farming.

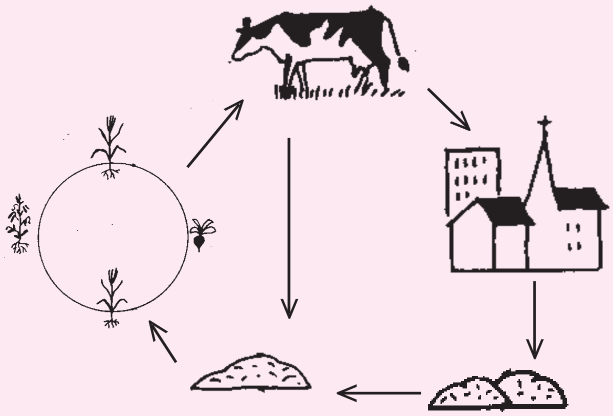
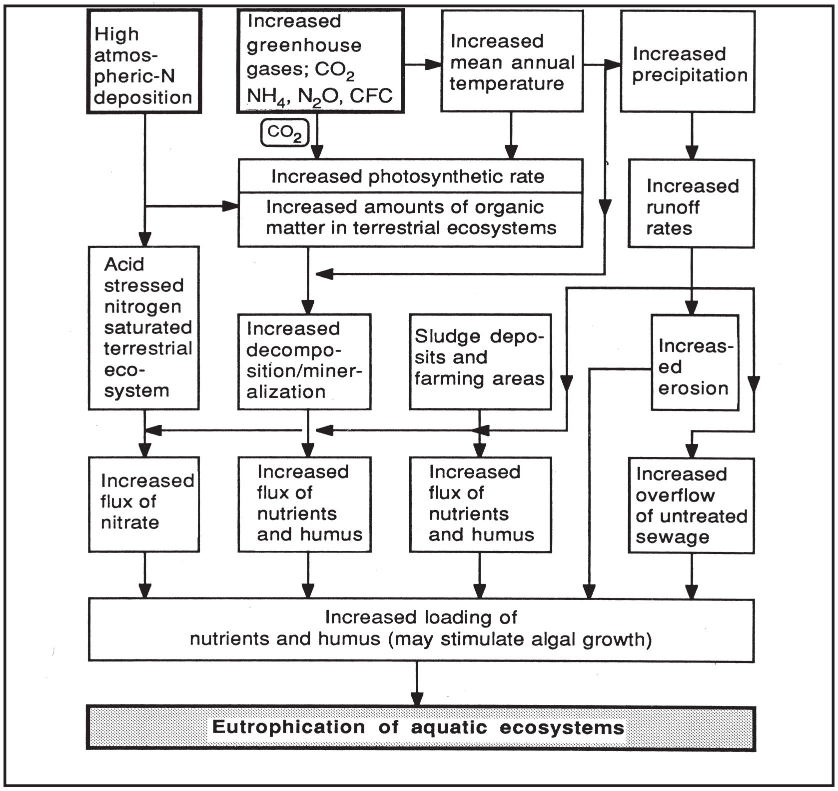


Figure 9.37. Ecological farming is based on recirculation of nutrients, that is, return of animal manure and organic waste from society (including sludge) to farmland. (Based on Bodin, 1997.)

Figure 9.38. Nitrogen deposition and climate change. Increased atmospheric nitrogen deposition and climate change is likely to lead to increased eutrophication. (Forsberg, 1991)



many countries the per capita consumption of N and P has increased due to an increased consumption of animal proteins, and a number of P additives in processed food and beverages. The over-consumption of these nutrients may be in the range of 15 – 30% (Fleckseder, 1994; Forsberg, 1994 a, b). Per capita supply of N and P in Sweden, calculated from national food balance data, shows an increase from 1960 to 1992 of about 20% for both of these elements (Becker and Robertsson, 1994).

Production and consumption of certain animal protein may show a dramatic loss of N (Figure 9.35). Thus, a Norwegian study shows that only 10% of the total inputs at the primary plant production level remains in the edible products that reach the consumers mouth (Bleken and Bakken, 1997). Fleckseder (1994) reported a corresponding value of 15% from Austria.

Having in mind a total number of people who are over-consuming N and P during a longer time period, it is apparent that this over-consumption will give a substantial nutrient supply and lead to increased eutrophication. There seems to be no official policy declaration with the aim of reducing losses of N and P due to over-consumption.

Global warming increases eutrophication

Human activities may result in increased global warming during the next century due to increasing emissions of CO_2 and other greenhouse gases, such as CH_4, N_2O, and chlorofluorocarbons. Numerical models of the global climate predict an increase in global mean temperature of between 1.5 and 4.5 °C, and for Fennoscandia an increase in mean annual temperature of 3-5 °C (Chapter 10). It is expected to result in both increased and reduced amounts of precipitation, depending on world region. In northern Europe, including the Baltic Sea area, increased amounts of water may be available for surface water and runoff. These changes will have a number of impacts, e.g., on geomorphological processes, natural ecosystems, agriculture, forestry, and on water resources.

Important effects of increasing atmospheric CO_2 content on plants may be increasing photosynthetic rates, productivity rates and water use efficiency. However, growth limiting factors may also appear.

Increased greenhouse warming will extend the growing season which will probably result in higher crop yields and forest production. The basically N-limited forest ecosystems may already be stimulated by the elevated load of atmospheric N. This trend may continue into the next century as well. Increased temperature will also speed up the decomposition and mineralization rates of the increased organic matter produced, resulting ultimately in increased amounts of available nutrients and humic material.

Atmospheric nitrogen deposition on large parts of southern Scandinavia is currently 10-20 kg per ha and year. Most of this deposition is retained in terrestrial ecosystems, but in recent years these systems appear to have become "saturated" with nitrogen. With this occurring, an increasing release of nitrogen may be expected, resulting in increased flux of nitrogen from soil to inland surface waters and ultimately to marine areas. This loading may continue into the next century as well.

The possible effects of an increasing greenhouse impact on eutrophication may be described through a number of processes coupled in series (Figure 9.36). An evaluation of the implications of climatic change for nutrient loading on Norwegian waters demonstrated, among other things, that if nitrogen saturation and mineralization of soil organic nitrogen increase, the future nitrogen loading on marine ecosystems could increase by 2-3 times. Thus, global warming may increase nutrient flux to surface waters, including the Baltic Sea, and thereby stimulate an increase in eutrophication.

Some countermeasures

The growing world population in combination with further increased urbanization makes it very difficult, with the policies used so far, to reduce large scale eutrophication of waterbodies. While awaiting methods to minimise the losses of nutrients in agriculture and effective systems for nutrient recycling, strong policies must be developed which can reduce waste of N and P. The philosophy must be to limit consumption as much as possible in all steps, in primary and secondary production in agriculture, and in the production and consumption of food and detergents. Therefore, all laundry detergents should be phosphate free, and all phosphate additives in foods and beverages should be eliminated. Today a large number of food products contain additives of phosphate and phosphoric acid. From environmental and natural resource points of view it is embarrassing that P is used for e.g., making ham more "juicy" (phosphate binds water), or to prepare Cola beverages with suitable pH by adding phosphoric acid (P concentration may be 180 mg/l). Strong policies are also needed to stop overconsumption of animal protein. By decreasing the intake of P (phosphate additives) and N (animal protein) one can expect a substantial reduction of the nutrient loading on our waterbodies.

The basic problem is to change nutrient flows from linear to cyclic. Return of sludge to farmland is one such basic requirement. Combustion processes that do not result in nitrogen oxidation is one more necessary step. Some of these are possible already with present technologies. But today, different systems in modern society, policies, technologies, and institutional organisations make it easier to live unsustainable than sustainable lifestyles. Therefore, it will be an enormous challenge to change this situation. It will also take time as the alternatives are not yet very clear. There are a number of barriers to overcome to reduce large-scale eutrophication, but also much opportunity for new policies and innovations.

Review questions

1. Explain what nutrients, macro-nutrients, and micro-nutrients are. Why do these in certain circumstances become damaging to organisms and ecosystems?
2. Describe and compare the main sources of nutrients in the biosphere, both natural and man-made.
3. Describe the nitrogen cycle in the environment, and main elements of the cycle using recent data from relevant databases, including nitrogen fixation, nitrification, and de-nitrification.
4. Describe the phosphorus cycle in the environment, and main elements of the cycle using recent data from relevant databases.
5. Compare the nitrogen and phosphorus cycles.
6. Define eutrophication of water, and identify the main changes in surface water caused by eutrophication of a pond, a lake, and the sea, and discuss the differences and consequences.
7. Describe eutrophication of land and its consequences, and identify the main changes in soil in forest, meadow, and urban areas, and discuss the differences and consequences.
8. Describe the nutrient flows from agricultural production. Give examples from various countries in the Baltic Sea region and describe policies that have been introduced to reduce the run-off of nutrients.
9. Comment on the world-wide dimensions of eutrophication.
10. Describe the problem of eutrophication of the Baltic Sea. What are the main causes and biological consequences.
11. Explain why the oxygen concentration varies with the seasons in the upper layers of the Baltic Sea, and give the reasons for oxygen depletion in bottom layers of the sea and consequences for living organisms.
12. Explain which methods are available to predict the level of eutrophication in a given area?
13. Describe what is meant with computer modelling of nutrient flows and eutrophication and give two examples.

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Internet resources

Algal Bloom Browser
http://wwwmarin.natgeo.su.se/~ab/

Alg@online Database
http://meri.fimr.fi/Algaline/eng/EnAlgaline.nsf

BED - Baltic Environmental Database
http://data.ecology.su.se/models/bed.htm

EcolIQ on Water & Wastewater
http://www.ecoiq.com/water/

EMEP - European Monitoring and Evaluation Programme
http://www.emep.int/

European Environment Agency
http://www.eea.eu.int/

Eutrophication in the Baltic Sea
http://boing.fimr.fi/index.html

Eutrophication of soil and water - Swedish EPA
http://www.internat.environ.se/index.php3?main=/documents/pollutants/overgod/eutroe.html

FAOSTAT Fisheries data
http://apps.fao.org/page/collections?subset=fisheries

GRID Arendal - United Nations Environment Programme
http://www.grida.no/

Harmful Algal Bloom Forecasting Project - NOAA Coastal Services Center
http://www.csc.noaa.gov/crs/habf/index.html

INCA - Integrated Nitrogen Model for European Catchments
http://www.rdg.ac.uk/INCA/

The IOC Harmful Algal Bloom Programme
http://ioc.unesco.org/hab/

MARE - Marine Research on Eutrophication
http://www.mare.su.se/english/

Science Traveller International
http://www.scitrav.com/wwater/waterlnk.htm

SMF - Stockholm Marine Research Centre
http://www.smf.su.se/english/indexeng.htm

Statistics Sweden, Land and Environment
http://www.scb.se/eng/landmiljo/landmiljo.asp

Swedish University for Agricultural Sciences
http://www.slu.se/eng/index.html

Glossary

algal bloom
mass development of microscopic algae over large areas of water that drastically reduces transparency and sometimes also creates surface scum and odours; some such blooms, created by so-called harmful algae, may be toxic for marine organisms and poisonous to people

atmospheric loading
man-made inputs of nitrogen to the atmosphere caused by emissions of nitrogen oxides from combustion of fossil fuels in factories and power stations, combustion of fuel in transportation, combustion of biomass, and evaporation of ammonia from manure on farms; the atmospheric contribution consists of wet (gaseous) and dry (particulate) depositions, which together constitute the total deposition of an element

biological N_2-fixation
the microbial process in which nitrogen gas is transformed into bioavailable N; important nitrogen fixers are blue-green algae

BOD – biochemical (biological) oxygen demand
the amount of oxygen used in biochemical and microbiological activity, usually measured for 5 days; used as an index of pollution of waters with organic compounds

computer modelling
mathematical modelling of processes, e.g. pollution processes, to better identify and understand the process of pollution, to predict future developments and identify the key measures needed to control pollution; the processes studied are often very complex and composed of a number of partial processes in complex interaction; a pollutant is described as distributed through a system of several sub-compartments, where it undergoes various changes in each such sub-compartment

denitrification
a bacterial processes, occurring in anoxic conditions, i.e. in bottom waters, in which nitrates (NO_3^-) are converted to nitrogen gas (N_2) which is released to the atmosphere

diatoms
mostly unicellular microscopic algae (*Bacillariophyta*) with a doubled cell wall built with silica; Si:DIN refers to the ratio of silica concentration to the number of diatoms

ecotone
an edge, often species-rich transition zone between different ecosystems, either natural, i.e. between a river and land or constructed, e.g. bushes left between cultivated fields

eutrophication
process causing a significant increase of plant matter in water or on land due to a high load of nutrients from antropogenic sources, which results in excessive bacterial growth and strong oxygen depletion; land eutrophication, especially due to a high load of nitrogen, causes a change of flora from species adapted to poor soils to those adapted to nutrient-rich soils (often much larger species)

Glossary

external loading
release of nutrients from external sources

fertilizer
mixture of nutrients, especially N, P and K (potassium) used in cultivation of crops

Haber Bosch process
an industrial technology for fixation of atmospheric nitrogen, reducing nitrogen to ammonia, powered by large amounts of fossil fuel; industrial fixation of atmospheric nitrogen is today of the same size as biological nitrogen fixation

internal loading
release of nutrients, mostly phosphorous, from the bottom sediments in lakes and the sea; internal loading may occur under anoxic conditions in deep water and on shallow, eutrophied bottoms at high summer temperatures

nitrates (NO_3^-)
salt of the nitric acid which is highly soluble; one of the most important constituents of fertilisers, leachates containing nitrates lead to eutrophication of water systems

limiting nutrient
nutrient limiting plant growth, which can cause eutrophication if added; most often nitrogen and phosphorus is limiting, but silica and trace metals may also be limiting

macro-nutrients
elements or nutrients necessary for growth in larger amounts; macro-nutrients include some metals - calcium, magnesium, potassium - the metalloid silicon, and the non-metals sulphur, nitrogen, and phosphorus

manure
faeces and urine from animals

micro-nutrients
elements necessary for growth in very small amounts; micro-nutrients include the trace metals, principally copper, iron, and zinc, as well as the non-metals boron, manganese, and selenium

mineralization
microbial activities in the soil occurring when air gets access to soil and nutrients bound to organic substances are released

nitrification
a bacterial processes in which, in aerobic conditions, ammonia (NH_3) is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-).

nitrites (NO_2^-)
salt of nitrous acid, highly soluble, easily oxidized to nitrates

NO_x, nitrous oxides
a mixtures of oxides of nitrogen produced in combustion of fuel with air in power plants and car traffic; with water in the air nitrous oxides form strong acids, nitrous acid and nitric acid, which are both eutrophying and acidifying

nutrients
organic and inorganic chemical compounds or elements necessary in various amounts to support normal living processes

Redfield value
ratio of nitrogen to phosphorus roughly describing the algal consumption pattern of these elements; in phytoplankton organic matter, there are on average 16 nitrogen atoms for one phosphorus atom, that is the Redfield value is 16 N : 1 P

sewage
waste water and excrement; sewage is a main source of discharges of nutrients into recipients, such as lakes and rivers

simulation model
semi-empirical model, aimed at a numerical reproduction of all the major physical, chemical, and biological processes that define a system, for example biogeochemical fluxes

sludge
residue after sewage treatment where nutrients, especially phosphorus, is enriched

systems analysis
analysis of a system using computer modelling

turnover rate
movement of nutrients or other chemical compounds in a biogeochemical cycle calculated from inflow and outflow from a given pool and its quantity

weathering
release of phosphorus from minerals and mineral particles in soil

world model
a systems analysis of the world as a whole, e.g. that published by the Club of Rome in the classic 1972 report "The Limits to Growth" that predicts a very bleak future for the world if pollution on the scale then would continue for about 100 years