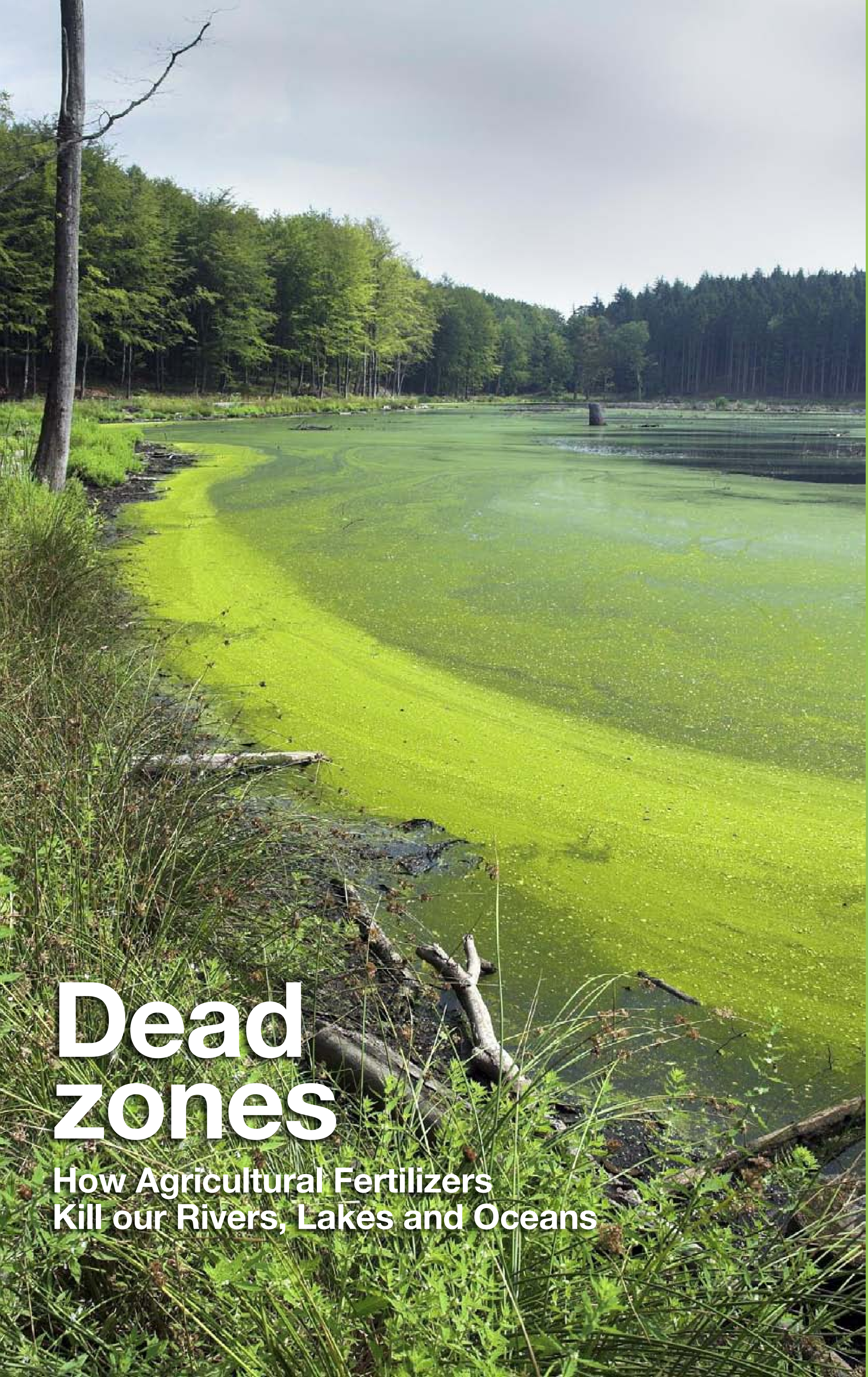

Dead zones

How Agricultural Fertilizers Kill our Rivers, Lakes and Oceans

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Introduction

Fertilizer run-off from industrial agriculture is choking the planet's oceans, rivers and lakes. Nitrogen and phosphorus pollution feed explosive algal blooms that suck the oxygen from the water as they grow. These algal blooms result in dead zones that have become a recurrent feature in every ocean and on every continent from the Gulf of Mexico to the Black Sea, from Canada's Lake Winnipeg to China's Yangtze Delta. As global warming heats our oceans, these problems will only worsen. Unless measures are put in place to control fertilizer usage, losses to biodiversity will continue to mount, coastal and inland fisheries will suffer and summer beaches could become toxic no-go zones devoid of life.

1 Definitions

ALGAL BLOOMS:
What are they?

An algal bloom is essentially a rapid and massive growth of minute plants that float in the water (phytoplankton) in rivers, lakes and oceans. There is a great diversity of algae that form blooms, with different colours, toxic properties and other traits, but generally each algal bloom event is caused by one or two species of algae. If algal blooms involve red algae, the blooms are also known as "red tides."

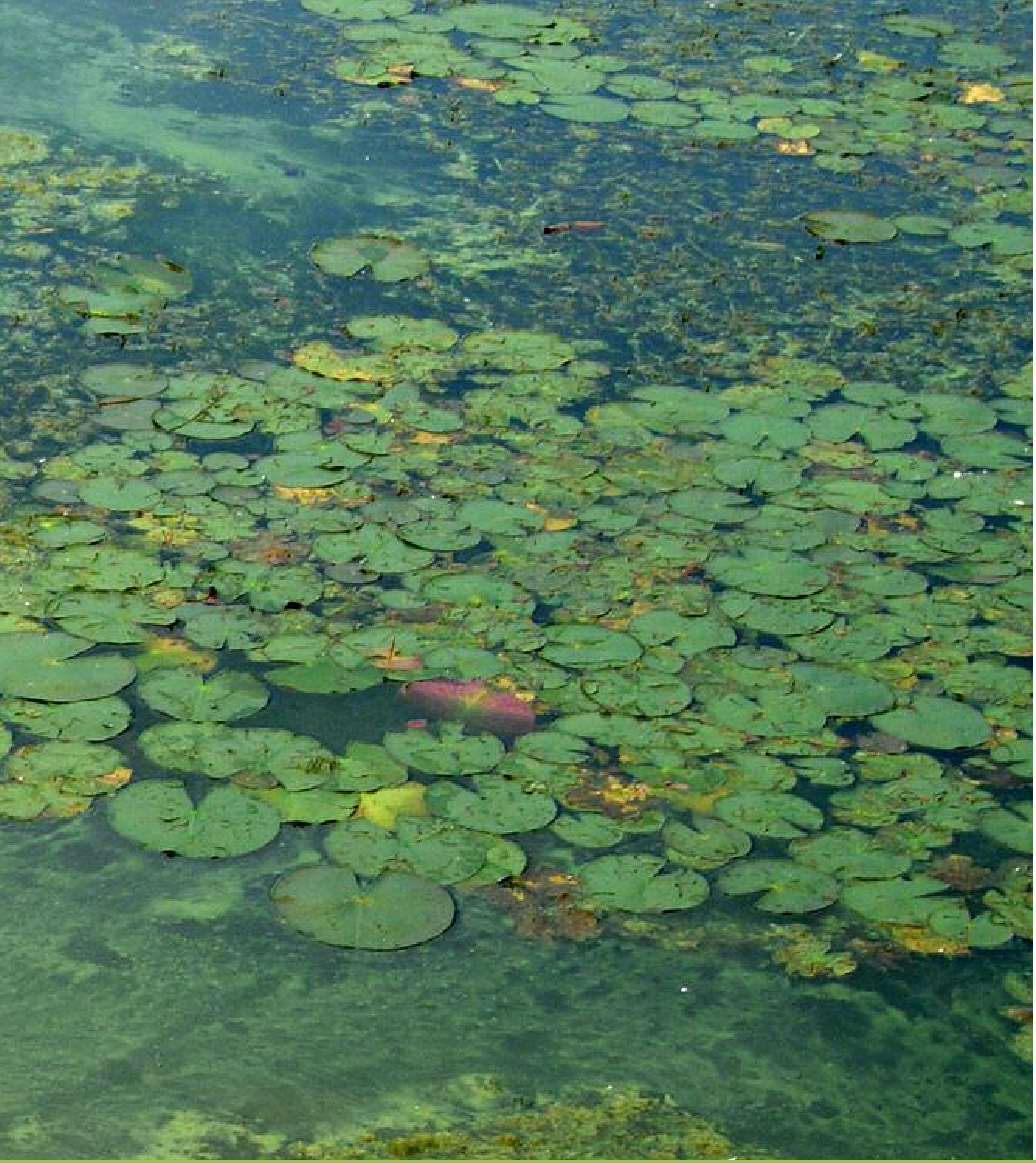
Some algal blooms are prompted by natural processes like the seasonal upwelling of nutrient-rich deep seawater (Kudela et al. 2005), but they are mostly the result of human-related nutrient pollution in the water and the consequent massive growth of organisms (Diaz et al. 2004, Dumont et al. 2005, Glibert et al. 2005). The more nutrients are available in the water, the more the algae can grow and develop thick blooms.

NUTRIENT OVERLOADING AND EUTROPHICATION

Nutrient pollution, in the form of nitrogen or phosphorous, reaches coastal waters from a variety of human sources including agriculture runoff of fertilizers into rivers, domestic and industrial sewage discharges and atmospheric pollution from burning of fossil fuels (Rabalais et al. 2002, Dumont et al. 2005, UNEP/GPA 2006). Eutrophication means an increase in nutrients in inland or coastal water which often cause the massive growth of aquatic organisms.

HARMFUL ALGAL BLOOMS AND RED TIDES:
1st consequence of nutrient overloading

Harmful algal blooms (HABs) refer to algal blooms that have negative effects. These may be direct effects, when the algae produce toxins that sicken or kill human and aquatic organisms. Indirect negative effects include declining fisheries and biodiversity in coastal areas, or depleting oxygen in the water creating dead zones in the oceans.



Red tides are simply algal blooms of reddish coloration, but algal blooms can be red, orange, brown or green. They occur when the microscopic algae grow in such concentration that their pigment becomes visible to the naked eye, but in spite of the term “tide” they have nothing specifically to do with tides.

DEPLETION OF OXYGEN AND DEAD ZONES: 2nd consequence of nutrient overloading

Dead zones in the oceans are coastal areas where the water closer to the seafloor is depleted in oxygen (Diaz 2001). Water with very low levels of oxygen is called hypoxic; when no oxygen can be detected, it is called anoxic. The lack of oxygen in hypoxic zones on the seafloor makes it impossible for fishes and invertebrates to survive, and thus the term “dead zone” refers to the fact that no living fish, crab or other animal can be found in these areas (Jackson et al. 2001, Rabalais et al. 2002). Oxygen depletion is likely to become a keystone marine impact in the 21st century (Jackson et al. 2001, Diaz et al. 2004). Many studies documenting change in marine ecosystems indicate that oxygen depletion is a major phenomenon that is the manifestation of nutrient overloading and eutrophication linked to human terrestrial activities (Diaz et al. 2004). There are now 199 documented dead zones related to human-caused eutrophication (Figure 1). Most dead zones are seasonal, appearing once a year usually in the warmer months after rainfall boosts nutrient runoffs, and others are permanent, like the one in the Baltic Sea (see Figure 4, which distinguishes between annual, permanent and episodic dead zones).

2 Sources of nutrient overloading and eutrophication

Both phosphorus and nitrogen are nutrients that are responsible for eutrophication worldwide, but nitrogen is one of the most important nutrients for ecosystem processes because it is often the most limiting nutrient, especially in estuaries and other marine areas (Diaz et al. 2004, UNEP and WHRC 2007). Phosphorus (mostly from fertilizers, sewage and detergents) also contributes to eutrophication, mostly in freshwaters. In many cases nitrogen and phosphorus pollution can also interact, so that the integrated management of both is needed in addressing environmental impacts (UNEP and WHRC 2007).

Nitrogen flow towards oceans is strongly increasing, a trend that is expected to continue. Since pre-industrial years, nitrogen flows have increased 15-fold in North Sea watersheds, 11-fold in the northeastern United States, 10-fold in the Yellow River basin, approximately 6-fold in the Mississippi River basin, 5-fold in the Baltic Sea watersheds, and approximately 4-fold in south-western Europe (UNEP/GPA 2006). Projections for 2030 show an increase in global nitrogen export to ocean areas of 14% compared to 1995 (UNEP/GPA 2006).

The main sources of nutrient overloading are as follows:

1. **Fertilizer runoff,** which is a major source of nutrients in many eutrophic areas and represents about 67% of nitrogen input in the Mississippi river flowing to the Gulf of Mexico (Rabalais et al. 2002, Rabalais 2007), and more than 50% of the nutrient inputs in the Baltic Sea (UNEP and WHRC 2007) and Taihu Lake (Liu and Qiu 2007).
2. **Domestic sewage,** including human wastes and phosphorus detergents.
3. **Industry,** including manufacturing of fertilizers, and wastewater discharges.
4. **Burning of fossil fuels,** which generally has a lower contribution, but can be very significant in certain highly industrialised areas, and represents about 30% of nitrogen input in the Baltic Sea and about 13% in the Mississippi River (Howarth et al. 2002).

Harmful algal blooms (HABs) are clearly linked to nutrient overloading, but other environmental factors influence their occurrence and intensity. For example, warmer temperatures stimulate algal growth and lack of windy weather prevents water from mixing, thus promoting stable conditions for bloom formation. Natural processes like the upwelling of deep-sea waters, or the fertilization of algae with iron—which enables algae to utilize nitrogen—carried in wind-blown dust from the Sahara, are also linked with toxic red tides and other HABs in specific regions.

Fertilizer runoff

Globally, and on every continent except Africa, synthetic nitrogen fertilizer is the single largest human-related source of nitrogen in coastal waters, representing about 40% of global anthropogenic nitrogen entering marine ecosystems (11 million tonnes of nitrogen per year). The other 60% comes from domestic and industrial sewage, animal wastes, growth of leguminous crops and atmospheric loads from burning of fossil fuels which combined add another 16 million tonnes nitrogen per year (Maranger et al. 2008). Fertilizer runoff is the dominant source of nitrogen pollution in South and Eastern Asia, Europe, and the Midwest in the US (Dumont et al. 2005; see Figure 2). South and Eastern Asia and Northern Europe have the largest rates of inorganic nitrogen exports to coastal waters in the world, up to 5000 kilograms (kg) nitrogen per square kilometre (km) of land area per year (Dumont et al. 2005).

One of the reasons behind this human-related massive nitrogen overloading is the inefficient way we use nitrogen to produce food: the amount of nitrogen used for food production is many times higher than the amount actually consumed by humans in foods, leaving the unused portion to pollute soils, waterways and the atmosphere. For example, less than 20% of the nitrogen applied on the farm to grow animal feed is consumed by the person eating meat from a typical industrial swine production system; the other 80% is lost into the environment (UNEP and WHRC 2007). Across the globe, in average, 12% of the synthetic nitrogen fertilizer applied to land directly reaches coastal waters, but that amount can be as high as 30% in areas of high runoff, as in cultivated high rainfall areas (Maranger et al. 2008). In the last 40 years, the amount of fertilizer directly entering

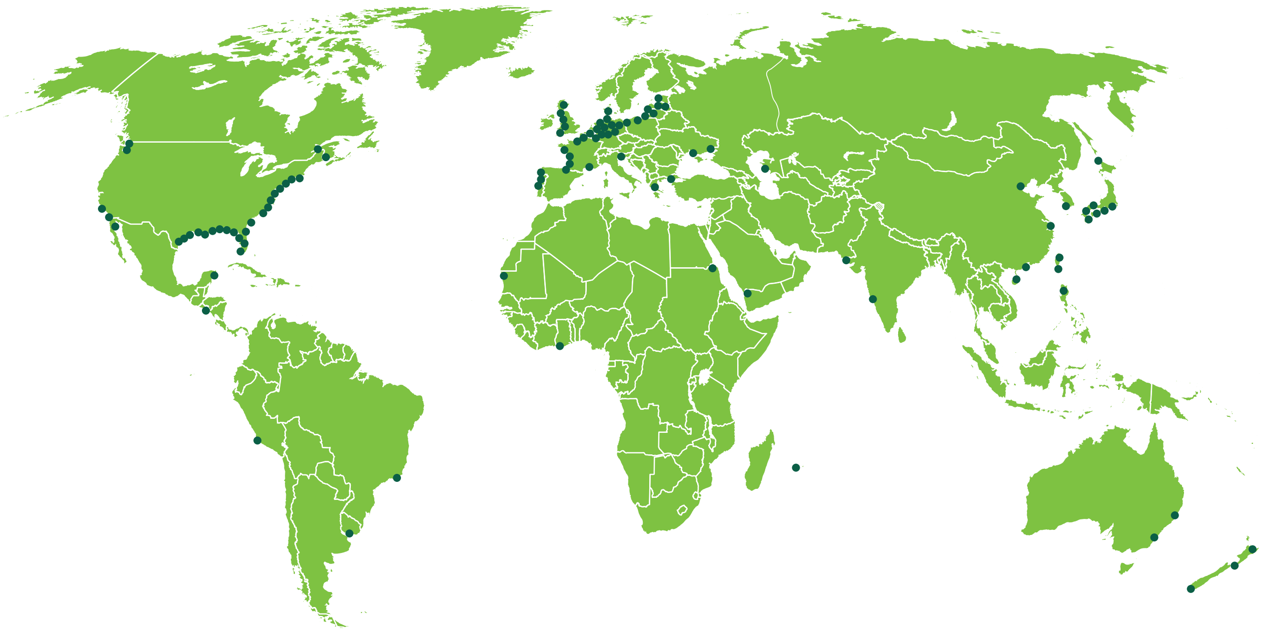
coastal waters has increased approximately 6-fold, due to the exponential growth of fertilizer use worldwide (Maranger et al. 2008). China, for example, which consumed less than 5 million tonnes of nitrogen fertilizer in the 1970s, now consumes more than 30 million tonnes per year, representing 25% of global nitrogen fertilizer consumption and leading to significant increased nitrogen pollution of its coastal waters (FAOStat 2008, Glibert et al. 2005).

Not only the amount, but also the type of fertilizer being used has changed dramatically, and this might help explain the increase of certain harmful algal blooms in some regions. Global use of urea has increased more than 100-fold in the past four decades and now constitutes more than 50% of the global nitrogen fertilizer use (Glibert et al. 2006). This increase in urea seems to be linked to the increase in the growth of specific HABs, because certain toxic and nuisance algal species may preferably use urea over other type of nitrogen compounds for their nutrition (Glibert et al. 2006).

For example, there is a correlation between the global increase in documented cases of paralytic shellfish poisoning—caused by several HAB species—and the global increase in urea use over the past three decades, as shown in Figure 3 below (Glibert et al. 2006). Although this is not a causal link between urea and HABs, it points to the effect that the massive worldwide increase in urea use could have on HABs.

Some of the clearest examples of the relationship between HABs frequency and increases in total nutrient loadings to coastal waters come from China. Since the 1970s, when escalation in use of chemical fertilizer began in China, the number of HAB outbreaks has increased over 20-fold, with blooms that appear now in more and larger areas, are more toxic and more prolonged (Glibert et al. 2005, UNEP and WHRC 2007). In northern European waters and in the Gulf of Mexico, HABs have also been clearly linked to increases in nitrate content in river flows (Glibert et al. 2005).

FIGURE 1 Global map of 199 coastal oxygen depletion zones related to human-caused eutrophication



SOURCE: UNEP AND WHRC 2007

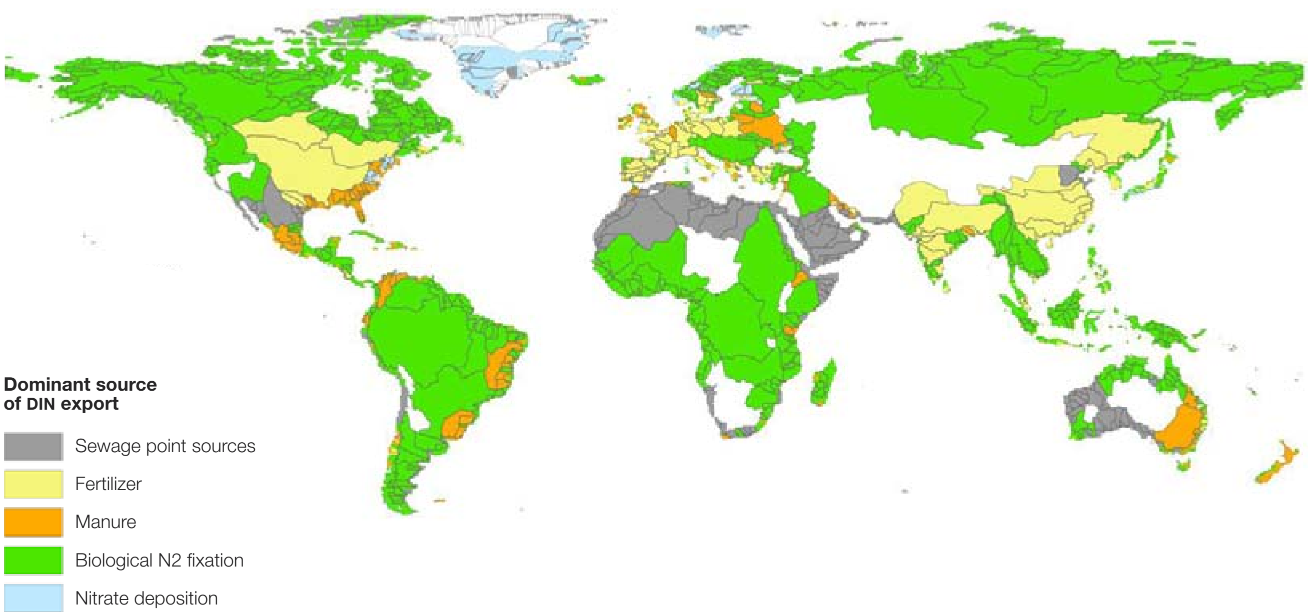
Nutrients from domestic sewage

The growing human population and its rising generation of sewage have also increased nutrient inputs to the environment. In developing countries, the majority of wastewater is released untreated directly into waterways. Fewer than 35% of cities in developing countries have any form of sewage treatment (UNEP and WHRC 2007). Where sewage treatment facilities do exist, they often provide only primary treatment, which does little to remove nitrogen. Even in the developed world, most sewage treatment facilities do not include the tertiary treatment step that removes most of the nitrogen. In some local cases, wastewater is the largest source of release of nitrogen into the environment, although regionally agriculture is still the largest contributor to nutrient overloading (UNEP and WHRC 2007).

Phosphorus

While industrial sources may be important locally, the two main sources of phosphorus inflows to surface water are municipal wastewater and agriculture. The main agricultural sources are from animal husbandry and fertilizer use. Phosphorus from detergents contributes an estimated 25% of the phosphorus in municipal wastewater in some European Union countries where phosphorus detergents are still used. Phosphorus discharges are reduced considerably by both banning phosphorus from detergents and making improvements to wastewater treatment. A number of countries have been successful in reducing eutrophication through implementation of measures to reduce phosphorus loads. Notable examples are Lake Geneva in Switzerland, Lake Erie in the United States, and Lake Endine in Italy. In all cases, the results indicate that a phosphorus reduction between 70% and 90% is necessary to significantly reduce eutrophication (Glennie et al. 2002).

FIGURE 2 Dominant sources of dissolved inorganic nitrogen (DIN) export in different river basins across the world



SOURCE: DUMONT ET AL. 2005

Of the phosphate produced by the world's industry today, about 80 to 85% is used in fertilizers. The next largest user, but relatively minor in comparison, is the detergent industry. Phosphate is also used in the manufacture of animal feed supplements (Chambers et al. 2001).

Nutrients from industrial sources

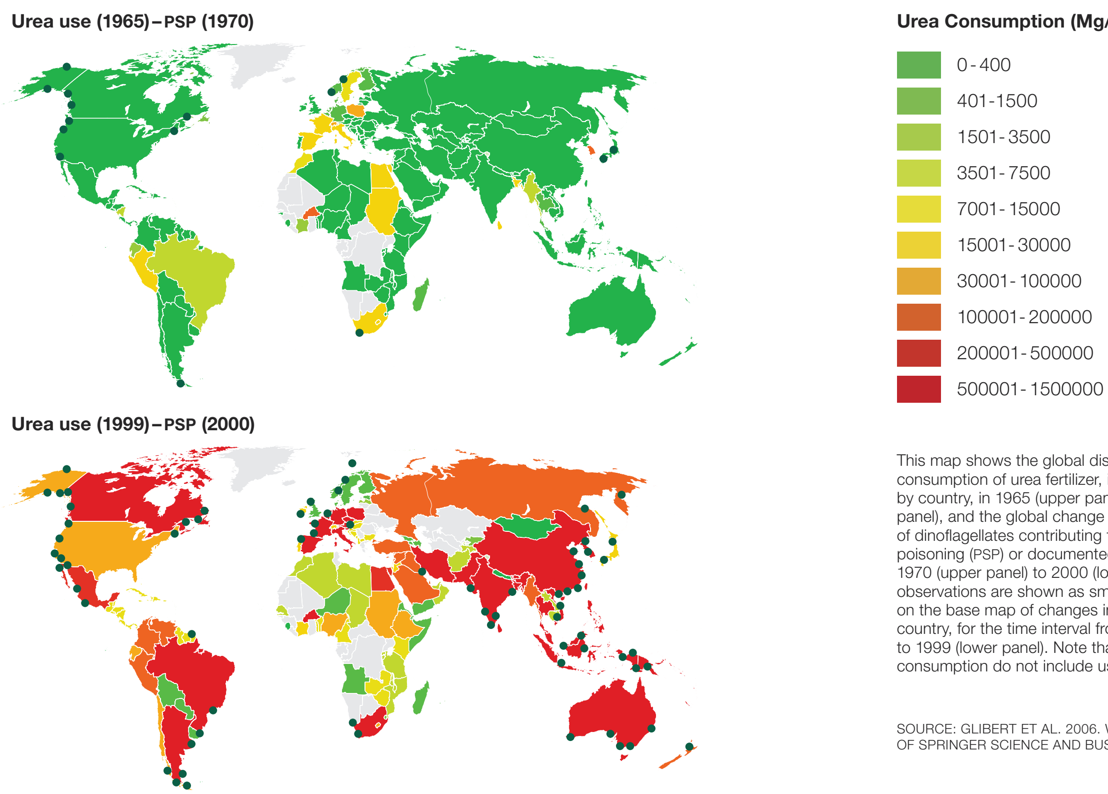
Nutrient pollution from localized industry discharges was of large relative importance until few years ago, especially in developing countries. Currently nutrient pollution from industry seems a smaller overall problem, due to the stricter controls in wastewater discharges and the increased relative importance of non-point sources (agriculture and livestock especially). However, in specific locations, industry discharges are still the major culprit in certain eutrophication and HAB events.

Many industrial manufacturing and processing plants use nitrogen and phosphorus compounds as base products.

Burning of fossil fuels

Burning of fossil fuels (both for transport and energy generation in power plants) creates nitrogen gasses (NO_X) that can directly deposit in water bodies or indirectly flow from landscapes where they were previously deposited. They represent a significant source of nitrogen in certain areas, like the Baltic Sea, where 30% of the nitrogen is estimated to come from this source, or in the Mississippi River, flowing to the Gulf of Mexico, where it represents 13% (Howarth et al. 2002).

FIGURE 3 Global distribution of the consumption of urea fertilizer and of observed incidence of paralytic shellfish poisoning



This map shows the global distribution of the consumption of urea fertilizer, in metric ton per year, by country, in 1965 (upper panel) and in 1999 (lower panel), and the global change in recorded observations of dinoflagellates contributing to paralytic shellfish poisoning (PSP) or documented cases of PSP, from 1970 (upper panel) to 2000 (lower panel). The PSP observations are shown as small circles superimposed on the base map of changes in global urea use, by country, for the time interval from 1965 (upper panel) to 1999 (lower panel). Note that these estimates of urea consumption do not include uses other than fertilizer.

SOURCE: GLIBERT ET AL. 2006. WITH KIND PERMISSION OF SPRINGER SCIENCE AND BUSINESS MEDIA.

In Canada, the massive increase in tar sand oil production in the west of the country has led to an increase in acid rain transporting sulphur and nitrogen gasses (NOx) to the east of the continent and in particular Quebec and Ontario (Government of Canada 2008). As a result, in 2007, the Quebec government's own records estimated that over 160 lakes or rivers were affected by algae blooms, including some in regions where there are no agricultural activities that could have caused the blooms (Government of Quebec 2007).

Influence of climate change

Global warming could potentially exacerbate the occurrence of harmful algal blooms in future years, since higher temperatures tend to stimulate algal growth and favour toxic algal species (Chu et al. 2007). Other physical factors affected by climate change could stimulate nutrient flows and eutrophication. For example, referring to the Gulf of Mexico, a group of scientists recently stated: "Future climate change, within the range likely to occur in the 21st century, could have profound consequences to hypoxia in the northern Gulf of Mexico. If changes result in increased precipitation, river discharge and nitrogen loading, hypoxia is expected to be more extensive, persistent and severe" (Rabalais et al. 2007).

MAIN EXAMPLES OF INDUSTRIES RESPONSIBLE FOR NUTRIENT DISCHARGES ARE THE FOLLOWING:

- **Fertilizer manufacturing plants:** ammonium nitrate, urea, phosphates, etc.
- **Pesticide manufacturing plants:** organophosphorus pesticides, but also nitrogen chemical compounds.
- **Food processing plants:** discharges of food wastes, sodium nitrite used in the commercial production of cured meat such as sausages.
- **Phosphorus detergent production:** sodium tripolyphosphate (STPP) still used as main detergent builder in many countries.
- **Industries using urea as base product:** fire retardant paints, tobacco products, cosmetic industry—moisturizing creams.

3 Oxygen depletion, dead zones and other effects

Dead zones in the ocean form when the millions of minute floating plants and animals (phytoplankton and zooplankton) that are associated with algal blooms die and sink to the deep sea floor where they are consumed by microbes. In turn, these microbes also grow dramatically, and consequently use up the oxygen in bottom waters. The oxygen content in fully oxygenated seawater levels is about 10 parts per million (ppm); once water oxygen levels fall to 5 ppm, fish and other marine animals have trouble breathing (Diaz 2001, Dodds 2006). Hypoxic zones are defined as areas where the oxygen level has fallen below 2 ppm. While fish swim away when levels fall below 2 ppm, other less mobile animals cannot escape and they begin to die at around 1.5 ppm oxygen (Diaz et al. 2004). Biodiversity is thus diminished on the seabed as many animals cannot survive, even though closer to the water surface there is still sufficient oxygen to support animal life.

Oxygen depletion around the world

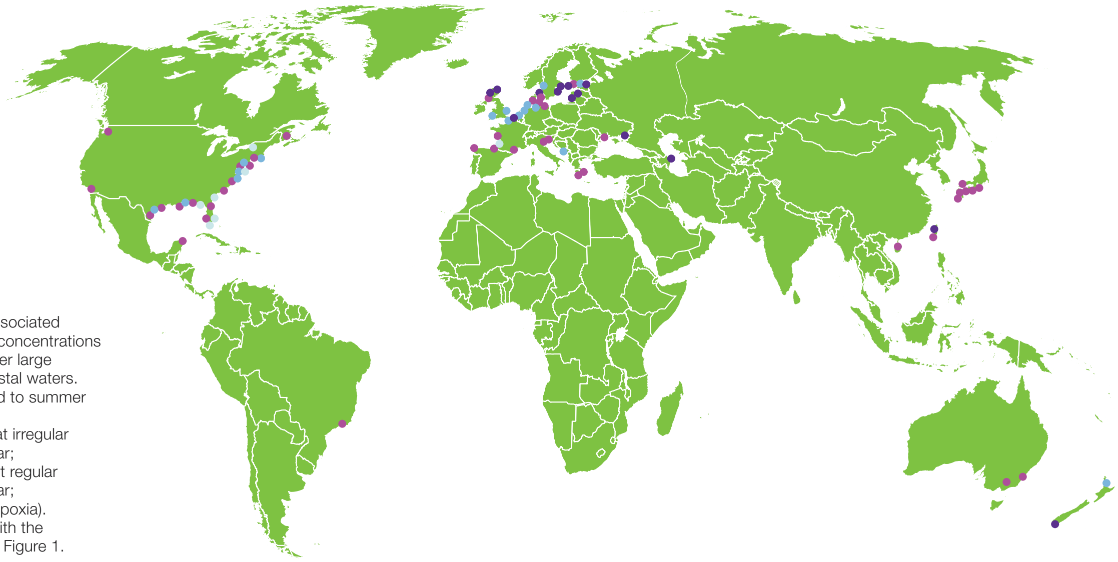
The worldwide distribution of coastal oxygen depletion is either centred on major population concentrations, or closely associated with developed river basins that deliver large quantities of nutrients (Diaz et al. 2004). In some regions, dead zones extend across vast areas, and the problem is growing worldwide. The number of dead zones has doubled every decade since the 1960s. The United Nations Environmental Programme estimated in 2006 that the number of dead zones has increased worldwide from 150 in 2004 to 200 in 2006—a 30% increase in just two years (UNEP 2006).

The largest dead zones are found in coastal areas of the Baltic Sea (84,000–100,000 km^2), northern Gulf of Mexico (21,000 km^2), and until recently, the northwestern shelf of the Black Sea (40,000 km^2). Smaller and less frequently occurring areas of hypoxia occur in the northern Adriatic Sea, the south North Sea and in many US coastal and estuarine areas (Rabalais et al. 2002). Recent research shows that

FIGURE 4 Global distribution of oxygen-depleted coastal zones as of 2003

Oxygen depletion

- Annual
- Episodic
- Periodic
- Persistent



The 146 zones shown are associated with either major population concentrations or with watersheds that deliver large quantities of nutrients to coastal waters. *Annual*—yearly events related to summer or autumnal stratification; *episodic*—events occurring at irregular intervals greater than one year; *periodic*—events occurring at regular intervals shorter than one year; *persistent*—all-year-round hypoxia). For an updated UNEP map with the current 199 dead zones, see Figure 1.

SOURCE: UNEP. 2003 GEO YEAR BOOK

hypoxic areas are now also occurring off South America, China, Japan, southeast Australia and New Zealand. Some of the more recent registered sites appear to be in the Archipelago Sea in Finland, the Fosu Lagoon in Ghana, the Pearl River estuary and the Yangtze River in China, and the western Indian shelf (see Figure 4) (UNEP 2006).

The UNEP map above (Figure 5) shows dead zones in the oceans as of 2003, distinguishing between persistent and temporary dead zones. For example, some of the dead zones in the northern Gulf of Mexico are dominant from spring through to late summer, but rare in the autumn and winter, while the dead zones in the Baltic are permanent year-around (Rabalais et al. 2002).

Dead zones and fertilizers

Accelerated growth of the hypoxia zone in the Gulf of Mexico follows the exponential growth of fertilizer use beginning in the 1950s (Rabalais et al. 2002). In the Baltic, there is clear evidence that excess use of fertilizers is associated with dead zones in bottom waters (Karlson et al. 2002). The dead zone in the northwestern Black Sea in the 1970s and 1980s covered up to 40,000 km^2; since then there has been some recovery, most likely due to the reduction in use of agricultural fertilizers. This occurred as a result of the economic collapse of the former Soviet Union and declining subsidies for fertilizers. Less fertilizer input to the Danube River was accompanied by signs of recovery of both open-water and seafloor ecosystems of the Black Sea. By 1999, the hypoxic area receded to less than 1000 km^2. However, according to a study published in 2001, there has been no recovery of seaweed beds and most fish stocks are still depleted (Rabalais et al. 2002). Dead zones in the Baltic and Black Sea led to the disappearance of bottom fisheries in these areas (Diaz 2001).

Biodiversity loss and jellyfish invasions

Besides the increased frequency and severity of HABs and dead zones, nutrient overloading has been also blamed for the disappearance of seagrass habitats and massive loss in coastal biodiversity (Diaz et al. 2004). Jellyfish invasions in coastal waters, like recent recurrent events in the Mediterranean, Chinese river estuaries and Japan coasts, are the result of a number of factors, but nutrient loading and eutrophication are at the root cause of the problem (Purcell et al. 2007). The consequences of overfishing can further exacerbate eutrophication impacts (Maranger et al. 2008). As humans continue to unsustainably exploit fisheries, jellyfish and plankton do not have to face their usual predators and competitors, which would usually regulate their population growth.

4 Examples of nutrient pollution, HABs and dead zones

China

Nutrient pollution and HABs are widespread in coastal and freshwater bodies in China. The three coastal regions with highest frequency of HAB outbreaks from 1933 to 2001 were (see Table 1):

- the Bohai Sea;
- in the East China Sea: Hangzhou Bay and the Yangtze River estuary; and,
- in the South China Sea: Pearl River estuary and the coast of east Guangdong.

During 2007, 82 cases of red tide were reported in Chinese coasts, covering 11,610 km^2 of seawater (Liang 2008). Besides being highly eutrophic and suffering from frequent HABs, the estuaries of China's great rivers (Yangtze and Pearl) have also developed into two new dead zones in the global oceans (UNEP 2006).

The three most polluted and eutrophic lakes are the Taihu and Chao lakes in East China and Dianchi Lake in Yunnan province in South China (see Table 1).

Fertilizers runoff, livestock, aquaculture, domestic sewage from cities and industrial discharges are the main sources of nutrient loading in Chinese water bodies. Nutrient discharges from industries have been reduced to a large extent, in the last decade, whereas nutrient loading from fertilizer runoff and from domestic sewage have increased and continue to be largely neglected (Dai et al. 2006, Tang et al. 2006, Liu and Qiu 2007, Qiu et al. 2007).

In the Pearl River estuary the key nutrient loading problems come from fertilizer runoff from farms in the middle and low reaches of the river, and sewage from the surrounded populated areas. More than 70% of the domestic sewage is discharged untreated into the Pearl River or its coastal water directly (Huang et al. 2003, Dai et al. 2006).

In the Bohai Sea, "*more than one fifth of the country's sewage is dumped in the Bohai Sea every year, probably making it a dead zone in 10 years if no measures are taken to check the pollution,*" according to a marine ecology expert quoted by a government agency (SEPA 2008). Until late 2005, 42% of cities in China (278 of the 660) did not have any wastewater treatment facilities, and more than half of all wastewater treatment plants in 30 big cities were running at less than 30% of the treatment capacity (Liu and Qiu 2007).

The consumption of chemical fertilizers has increased dramatically in recent years in China, and researchers show that between 55 and 75% of the nitrogen and 75 and 90% of the phosphorus in fertilizers is not used by the crop and will partly reach water bodies through runoff (Liu and Qiu 2007). It is estimated that nearly 40% of the nitrogen and phosphorous in Dianchi Lake and more than 50% in Taihu Lake is from such non-point source pollution, mostly from agriculture (Liu and Qiu 2007). A new study published in the Chinese Journal of Ecology also showed that nitrate from farmland fertilisation is a main source of nitrogen pollution in Taihu Lake, followed by domestic sewage and livestock manure. See summary of pollution sources on HABs in Table 1.

India

In India there has historically been very limited scientific research in the occurrence and biology of harmful algal blooms (Bhat and Matondkar 2004). However, there are examples of red tides being reported both in the East and West Coast of India. Recently, HABs have been pointed out as the possible cause of poisonings and deaths after the consumption of shellfish in different parts of the state of Kerala over the years (Daijiworld.com 2008). In October 2006, the United Nations Environment Program (UNEP) declared a new dead zone in the ocean, situated in the western Indian shelf (UNEP 2006).

TABLE 1 Main locations of eutrophication and HABs in China

LOCATION OF HABS	MONTHS OF PEAK	MAIN NUTRIENT POLLUTION SOURCES	HABS OCCURRENCE AND EFFECTS
COASTAL WATERS			
Bohai Sea (worst in Yellow River estuary, Liaodong Bay, Bohai Bay)	July–August	Fertilizer runoffs, industrial discharges and domestic sewages. Surrounding land is home to 21% (~300 millions) of the Chinese population	HABs increasing in frequency, often accompanied by massive seafood kills
East China Sea (worst in Yangtze River estuary, Zhejiang eastern coast)	May–June	Yangtze River flows with fertilizer runoffs, industrial discharges and domestic sewages. The river nitrate concentration and flux have increased about 10-fold from 1968 to 1997	From 2000 to 2004: 246 HABs reported (compared to 111 HABs in the 1990s)
South China Sea (worst in Pearl River estuary, Shenzhen coast)	March–May	Fertilizer run-off from farms in the middle and low reaches of the Pearl River, industrial discharges and sewage from the surrounded populated areas	About 15 HABs reported every year from 1998 to 2003. In 1998, a massive HAB near Hong Kong killed ~ 80% of the fish farm stock
FRESHWATER BODIES			
Taihu Lake	June	> 50% from non-point pollution (agriculture from the western watershed, domestic sewage and aquaculture). Nutrient inputs from industry discharges have largely declined in the last decade	Massive increase in the last decade, now persisting throughout the summer. Microcystins, potent liver toxin poisoned water supply
Chao Lake	July–Sept.	Mostly from non-point sources (fertilizers and domestic sewage). Nutrient load from point sources has been cut down by 40% since the late 1970s	Highly eutrophic sine 1990s, HABs increasing in frequency and extension in last years
Dianchi Lake	April–May	~ 40% from non-point pollution (fertilizers) and also domestic sewage. *"clean-up measures have failed because they have focussed almost exclusively on industrial point sources and not on agricultural runoff or domestic sewage pollution"* (Guo 2007)	Highly eutrophic sine 1990s, HABs increasing in frequency and extension in last years
Xiao River (Three Gorges Dam)		Fertilizers runoff, industrial discharges and domestic sewages.	HABs downstream from the Three Gorges and a deterioration in aquatic life

Philippines

HABs have been recognized as a catastrophic phenomenon that has affected public health and economy in the country since 1983 (Relox and Bajarias 2003). The Philippines' shores have experienced more than 120 outbreaks of red tides and other harmful algal blooms in coastal waters between 1990 and 2003, most of them in Manila and Masinloc bays (Wang et al. 2008). In Manila Bay, toxic blooms have been increasing since the first recorded occurrence in 1983 (Sombrito et al. 2004) and 80% of blooms have occurred during the last decade (Wang et al. 2008). In Laguna de Bay, the largest freshwater lake in the country, a regular bloom of the toxic blue-green algae *Microcystis aeruginosa* is experienced during the months of May to July or from September to November, varying from year to year (Baldia et al. 2003). Toxins produced by the blooms could endanger fish produced in aquaculture, the major economic activity in the lake. Eutrophication caused by organic and nutrient discharges from aquaculture and agriculture seems to be the major causes of algal blooms in fresh and coastal waters in the Philippines (Wang et al. 2008).

Harmful algal blooms have adverse effects on the marine resources, human health and economy of the country. Harmful algal blooms in the Philippines do not only pose a public health hazard but a major economic threat as well. Between 1983 and 2002, a total of 2,122 paralytic shellfish poisoning (PSP) cases, with 117 deaths, affecting all age group, were reported (Bureau of Fisheries and Aquatic Resources 2003). The occurrence of HABs has been responsible for the economic losses in the fisheries sector of the country, particularly the shellfish industry. The 1983 outbreak in central Philippines resulted in a loss of 2.2 million pesos and there was a dramatic decline in demand for fishery products during 1988 in Manila Bay; it caused extensive economic damage, since prices of all seafood dropped to almost 40% of the normal price.

Thailand

Recent studies in Thai reservoirs have found frequent HABs in freshwater bodies (Peerapornpisal 2006). Researchers have found proliferation of the toxic algae in reservoirs in Chiang Mai (Mae Kuang Udomtara Dam) and Nakhon Pathom (Bang Phra reservoir) (Peerapornpisal et al 1999, Chantara et al 2002).

The Gulf of Thailand has been a major marine resource for Thai people during centuries. However, agricultural and industrial developments have made eutrophication the most serious problem of the inner Gulf of Thailand today (Menasveta 2001, Cheevaporn and Menasveta 2003). The runoff from Thailand's four principal rivers ends up in the Gulf, causing eutrophication. The Chao Phraya is the most polluted of the four rivers, particularly in the river estuary area, due to the urban and industrial expansion. The Ta Chin is becoming increasingly polluted due to accelerated agricultural and industrial development as well as urban expansion from the Bangkok area. On occasion, paralytic shellfish poisoning (PSP) after the consumption of contaminated mussels in the red tide area of Pranburi river estuary has occurred, even causing human deaths (Menasveta 2001). Anoxic conditions due to algal blooms could cause massive fish death: in August 1991, there was a mass fish kill in the coastal area of Cholburi due to a vast red-tide blooming of *Noctiluca* covering the area from Bangsan district to Pattaya (Menasveta 2001).

Rate of occurrences of plankton bloom has been increasing in the last decades in the Gulf of Thailand (Singhasaneh 1995). Two species of blue-green algae (*Trichodesmium erythraeum* and *Trichodesmium thiebautii*) and *Noctiluca miliaris* were found to be the cause of coastal algal blooms (Singhasaneh 1995). Red tides were often observed during the period of December to February in the western part of the inner Gulf, whereas in the eastern part, blooms were often observed during the period of March to August.

Europe

In the Mediterranean Sea, concentrations of nutrients in rivers are generally at least four times lower than in rivers in northwest Europe, but there is evidence of an upward trend in both nitrogen and phosphate concentration in water flowing into coastal areas.

In the Black Sea, nitrogen levels are four times higher than they were in the 1960s. There is substantial evidence that this eutrophication is the result of large increases in the discharge of nitrogen and phosphorus to the Black Sea from the 1960s and 1970s (Mee 2001). Until recently, the northwestern shelf of the Black Sea was one of the largest dead zones worldwide (40,000 km^2). However, important reductions have taken place since the political and economic changes in the former Soviet Union and declines in subsidies for fertilizers. Less fertilizer input to the Danube River was accompanied by signs of recovery of both open-water and seafloor ecosystems of the Black Sea. However, according to a study published in 2001, there has been no recovery of seaweed beds and most fish stocks are still depleted (Rabalais 2002). Nitrogen from rivers represents 65% of totals, and 70% of this comes from the Danube River alone. Now that many central and eastern European countries have joined, or are in the process of joining, the European Community, the Black Sea will be influenced by the Community's common policies and regulations. As new member countries seek to have the same technologies and industrial agriculture of other members, the slow recovery of the northwestern Black Sea shelf will be endangered (Mee et al. 2005).

The Baltic Sea has changed from a nutrient-poor clearwater sea in the 1800s into a nutrient-rich eutrophic marine environment, due to excessive inputs of both nitrogen and phosphorus. In the Baltic Sea, nitrogen from rivers constitutes 69% of total nitrogen inputs, and atmospheric inputs (mostly from burning of fossil fuels) 31% of the total. The Baltic Sea region is one of the most naturally sensitive to oxygen deficiency in Europe and it is one of the most polluted seas in the world, according to experts in the Helsinki Commission (Helcom), the governing body for the protection of the Baltic Sea.

Helcom assessments clearly show that agriculture is one of the main sources of nutrient pollution entering the Baltic Sea: more than 50% of the nitrogen and phosphorus loads entering the sea by waterflow come from agriculture (UNEP and WHRC 2007). Helcom's current efforts are mainly focusing on the identification of further measures to reduce loads from agriculture in the different parts of the Baltic Sea catchment area. However, other nutrient sources, such as municipalities, scattered settlements and burning of fossil fuels still contribute significantly to the total inputs, and must also be considered to reduce overall nitrogen pollution. The progress in reducing nutrient loads from point sources such as municipal and industrial wastewater treatment plants has been good, with the 50% reduction target for phosphorus achieved by almost all the contracting parties (UNEP and WHRC 2007). However, other non-point pollution sources of nutrients, like agriculture, have not shown much progress.

According to Helcom experts, "*over-enrichment, meaning there are too many nutrients in the Baltic Sea causes a situation with algae blooms in the summer, which leads to depleted oxygen in some areas. This has an effect on biodiversity. For instance, cod cannot lay their eggs at the bottom of the sea because eggs need oxygen."* (Gunter 2005). In the eastern Baltic Sea a permanent dead zone covers up to 100,000 km^2. Blooms of blue-green algae in the Baltic also lead to regular beach closures and fish kills.

United States: Gulf of Mexico

In the United States, diffuse nitrogen and phosphorus pollution has increased dramatically, causing eutrophication, harmful algal blooms, dead zones, coral reef destruction, loss of sea grass and kelp beds, fish kills, shellfish poisoning, and seabird and marine mammal deaths (UNEP/GPA 2006). Human activities have increased nitrogen flux in the Mississippi River basin about four-fold. The single largest coastal system affected by eutrophication is a large dead zone in the Gulf of Mexico. In the early 1990s it was estimated to be 9,500 km^2 and in 2000 and 2007 it reached 22,000 km^2 (Rabalais 2007). "*Most of the nutrients that get to the Gulf come from agricultural activities*", says Dr. Nancy Rabalais, Director of Louisiana University's Marine Consortium and an expert on the Dead Zone. According to one of her recent publications, 67% of the nitrates in the basin are of agricultural origin, from the vast farming areas all along the Mississippi River.

Mexico: Gulf of California

Scientist estimate that nearly 75% of the nitrogen applied in fertilizer in the Yaqui Valley in western Mexico is lost into the atmosphere and runs off in surface waters. Year after year, an estimated 11,000–22,000 tons of nitrogen are washed into the sea. This triggers a particularly dramatic effect in the nitrogen-deficient waters of the Gulf of California, stimulating algal blooms within days of fertilisation and irrigation.

In 2005, a team of researchers from Stanford University in the United States demonstrated the close correlation between overuse of nitrogen fertilizer and explosive algal growth in coastal waters through satellite pictures (Beman et al. 2005). The images show thick algal bloom right off

the coast, fuelled by nitrogen runoff from wheat fields. The researcher measured algal blooms as big as 577 km^2 in the Gulf of California, which is one of the most productive and biologically diverse marine ecosystems in the world. More species of whale and dolphin feed and breed here than anywhere else. Nearly 900 fish species and 34 species of marine mammals swim in these waters, and more than 800 of the Gulf"s species are found nowhere else. Hundreds of species of birds, both migratory and resident, nest in mangroves and coastal lagoons. The effects of the regular algal blooms on this unique diversity are potentially significant.

From April to May 2006, local scientists documented three HAB events of yellow-brown colour, in Sinaloa. In May 2006, one of these blooms provoked a massive fish mortality, accounting for the accumulation in the beach of about 60 tonnes of fish, distributed on 3 kilometres of beach from Las Cabras to El Palmito del Verde, and which was the second fish mortality in the area associated with this type of HAB since 2004 (Cortés-Altamirano et al. 2006).

Canada

Canada has suffered multiple events of harmful algal blooms recently, especially in lakes and rivers in Quebec and Manitoba. Summer of 2007 saw the massive occurrence of blue-green algal blooms in many Canadian lakes, causing huge environmental impacts and economic losses. In addition, eutrophication events are increasingly appearing in rivers and coastal waters.

Since the occurrence of natural phosphorus in Canadian freshwaters is limited, in general the main cause behind algal blooms in Canadian lakes and rivers seems to be phosphorus pollution from human activities (Chambers et al 2001). In order to preserve Canadian freshwaters, stopping phosphorus pollution is an urgent priority. However, nitrogen pollution is also very high in the country, and it is causing problems like acid rain, eutrophication and algal blooms, especially in marine estuaries (Chambers et al 2001). These problems are very difficult and expensive to control once they have reached critical stages, and it is environmentally urgent and economically sensible to stop nitrogen pollution before the problems become acute (Schindler et al. 2006). Algal blooms and accompanying summer fish kills and human poisonings have been observed both in east and west Canadian marine estuaries (Chambers et al. 2001).

In Lake Winnipeg, concentrations of total nitrogen and phosphorus have approximately doubled in less than 10 years. The current state of the lake with respect to nutrient concentrations and algal blooms is roughly the same as Lake Erie was at the height of the drastic eutrophication problem in the early 1970s (Schindler et al. 2006). In 2007, the Quebec government's own records estimated that over 160 lakes or rivers were affected by algae blooms, including some in regions where there are no agricultural activities that could have caused the blooms (Government of Quebec 2008). Animal farming, and hog farming in particular, remain a major source of excessive phosphate in several watersheds in Quebec. However, a massive increase in tar sand oil production in the west of the country has contributed to an increase in acid rain in the east of the continent and in particular in Quebec and Ontario. As well, many of the lakes in western Canada have also undergone moderate to severe eutrophication as a result of conversion of land to agriculture and subsequent fertilization runoffs (Schindler et al. 2006).

The **agricultural sector** is responsible for about 82% of the phosphorus and 49% of the direct nitrogen pollution, mostly through runoff from fertilized soils and animal husbandry (Chambers et al. 2001, Janzen et al. 2003). Additional indirect nitrogen atmospheric deposition from agriculture gas emissions, such as ammonia and NO_x, would bring the total of countrywide nitrogen loading resulting from agriculture to 80% (Chambers et al. 2001). The most rapidly increasing source of nitrogen pollution in Canada is from agriculture. Both the use of commercial fertilizers and the production of manure from livestock husbandry have increased very rapidly. The increases in nitrogen are much more rapid than those in phosphorus and potassium, the other two main elements in commercial fertilizer. Since records began in 1950, nitrogen fertilizer production in Canada has increased about 75-fold, while uses of phosphorus and potassium have increased by only 5- and 7-fold, respectively (Schindler et al. 2006).

The Canadian Government has recently announced it will limit the amount of **phosphorus in detergents,** so that by 2010, all laundry and dishwasher detergents sold in Canada will contain no more than 0.5% phosphates, by weight (the current limit is 2.2%, by weight). However, these measures might not have a significant result, since the impact of phosphorus detergents on overall nutrient overloading of Canadian waters is relatively very small compared to agriculture runoff. In 1996, the average contribution of detergents to phosphorus pollution in Canadian municipal wastewaters was only 8% (Chambers et al. 2001). Besides, municipal water discharges only contribute 12% to total phosphorus pollution, compared to 82% from agriculture. Thus, overall, contribution of phosphorus detergents would represent only about 1% of total phosphorus pollution in Canadian waters.

After direct losses from agriculture, **nitrogen atmospheric deposition** (both from ammonia and NO_x gasses) is the second largest contributor to nitrogen pollution, with up to 30% of total nitrogen loading, mostly from ammonia from livestock manure, followed by manufacturing of commercial fertilizer (Chambers et al 2001). Ammonia emissions increased by 9% between 1995 and 2000, largely in agricultural areas of the west (southern parts of the Prairie Provinces and the lower Fraser River watershed, where agriculture is concentrated). Ammonia emissions are expected to increase by 50% between 2000 and 2020, largely as the result of the increasing intensity of livestock and poultry production and commercial fertilizer and pesticide manufacturing (Schindler et al. 2006).

Increased demands for meat and decreased financial returns per animal have caused an **explosive growth in livestock** in Canada. From 1996 to 2001, Canadian cattle increased by 4.4%, hogs by 26.4%, and chickens by 23.4%, despite a human population growth of only 4.0% (Schindler et al. 2006). Hogs are particularly large sources of phosphorus and nitrogen (Chambers et al. 2001). Nitrogen applications of both manure and commercial fertilizer are high, and in most cases, in excess of plant needs. Most notably, areas with high populations of livestock, like southern Alberta, southern Ontario and Quebec, and the lower Fraser Valley and Okanagan regions of southern British Columbia, have nitrogen applications, in the form of manure, of 1000 kilograms and more, per hectare. Commercial fertilizer use in Canada has also increased by 20 to 30% every 5 years (Schindler et al. 2006). In most regions of Canada, regulations for discharge of animal wastes are rudimentary; most wastes are simply spread or sprayed on the land. Hog operations usually discharge to surface lagoons, which have high ammonia losses to the atmosphere. Timing and rates of manure application are not well regulated (Schindler et al. 2006). Riparian corridors and wetlands are filled and destroyed in many regions. On average, 70% of wetlands in southern Canada have been destroyed, with little regard for their role as important nitrogen sinks or sites of denitrification. As a result, nitrogen has increased greatly in many surface waters. Phosphorus has also increased, leading to rapidly increasing eutrophication (Schindler et al. 2006).

NO_x emissions from electricity generation, vehicles, and oil and gas industries are also important contributors of nitrogen atmospheric deposition. Vehicles emit almost 50% of total NO_x emissions in Canada, followed closely by the oil and gas industries. Countrywide emissions of NO_x are expected to increase 17% by 2020, due to oil and gas extraction in the west and to coal-fired electrical power (Schindler et al. 2006). This estimate may be low, due to rapid population growth and massive developments in the Alberta oil sands, which are expected to cause enormous increases in nitrogen emissions to the atmosphere (Schindler et al. 2006). The Athabasca oil sands in northeastern Alberta are under rapid development and more oil sands plants are now operating or under construction. Huge trucks capable of carrying hundreds of tonnes of sand each are expected to produce NO_x that will cause nitrogen emissions to increase by 359% over 1998 values in the near future (Environment Canada 2003, Schindler et al. 2006).

Due partly to the **transport of acid rain** from west to east on the prevailing winds, the regions with highest nitrogen atmospheric deposition in Canada are in the east of the country, especially in the southern part of Ontario and Quebec provinces (Aherne and Watmough 2006). At least 860,000 km^2 of Quebec (1/4 of the territory) is affected by this phenomenon (Government of Canada 2008, cited in *Le Devoir* 2008). In Manitoba, the southeastern region of the province (south and east of Lake Winnipeg) greatly exceeds the critical maximum load of nitrogen deposition in forest soils (Figure 11, p. 31, in Aherne and Watmough 2006), which could endanger the future of forest and aquatic ecosystems in the area (Boggs et al. 2005). Because the Canadian Government decided to use sulphur emissions as the “yard-stick” for controlling acid rain in the last decade, nitrogen deposition may undermine some of the benefits of controlling sulphur emissions (Environment Canada 1999). In fact, it seems that nitrogen deposition has not been reduced as a result of measures to control sulphur emission and acid rain (Watmough et al. 2005).

Aquaculture contribution to nutrient pollution in surface waters is growing quickly. In 1996, aquaculture contributed about 1% of the nitrogen and phosphorus pollution in surface waters (Chambers et al. 2001), but rapid intensification of fish farming is quickly affecting Canadian waters. Along Canada's coasts, the intensification of salmon farm operations has led to significant contributions of nutrients to the surrounding environment, resulting in nutrient pollution and excessive algae growth (Mente et al. 2006; CCNB 2004; Robinson et al. 2004; Strain 2005; Strain and Hargrave 2005). The most frequently observed impacts occur on the sea floor in areas under aquaculture cages, as the result of nutrient pollution and oxygen depletion and, in extreme cases, resulted in the creation of a dead zone devoid of life beneath cages, surrounded by an area of decreased animal diversity (Goldburg et al. 2001). Research near finfish farms in the Bay of Fundy in the 1990s showed that diversity of animal fauna (macrofauna) was reduced close to farms throughout the area and, after five years of operation of farms, changes were documented up to 200 meters away from cages (Fisheries and Oceans Canada 2003).

Aquaculture wastes release nitrogen and phosphorous into the water, but because its wastewaters are poor in silica, aquaculture creates conditions less favorable to diatoms and more favorable to the slow growing phytoplankton (dinoflagellates and cyanobacteria) (Mente et al. 2006).

The rapid growth of such species as a result of nutrient pollution, in combination with other factors, has led to harmful algal blooms in the inter-tidal zone in the form of dense, green macroalgal mats (usually *Enteromorpha* or *Ulva* species) covering the seabed. An increase in *Enteromorpha* mats, covering more than 30% of the sediment, has been found adjacent to salmon farms in the Bay of Fundy, impairing growth rates of mollusks due to the creation of low oxygen conditions within and below the mats (Fisheries and Oceans Canada 2003). A salmon farm of 200,000 fish releases amounts of nitrogen and phosphorus roughly equivalent to the nutrient waste in the untreated sewage from 20,000 and 25,000 people, respectively. The 49,600 tonnes of farmed salmon produced in British Columbia in 2000 contributed as much nitrogen as the untreated sewage from 682,000 people, and as much phosphorous as the sewage from 216,000 people (David Suzuki Foundation 2008).

1 The major manufacturers of laundry detergent (Proctor & Gamble, Lever Brothers) have eliminated phosphorus from laundry detergents sold in North America. Other manufactures that have not changed their formulations represent only about 5% of the market (Chambers et al 2001).

2 Alberta has the most cattle; 6.4 million in 2001, an increase of 11.3% since 1996. The stated goal of the Alberta government is to double that 2001 number. Hog increases have been greatest in Quebec and Manitoba, but numbers in Alberta, Saskatchewan and other provinces have also increased substantially. Chicken numbers have increased most rapidly in British Columbia, by 37% over the same 5-year time period (Schindler et al. 2006).

5 Mitigation options

Since nutrient loading is the root cause in most of the HABs events and dead zones worldwide, the control of nutrient pollution from human-related activities is the most short-term and efficient mitigation option for eutrophication and HABs problems. The following mitigation options stand out.

1. Eliminate human-related nutrient pollution (nitrogen and phosphorus) at their main sources; these would be specific to the HAB or dead-zone event:

a. **Stop fertilizer runoff** from farms by promoting and establishing sound ecological agriculture practices as follows:

- Eliminate overuse of fertilizers and ensure that farmers use only the minimum amount necessary and in a non-polluting way. If applicable in the specific country or region, eliminate fertilizers subsidies, which promote the overuse and misuse of fertilizers, and implement strict, enforceable fertilizer reduction policies.
- Avoid any losses of fertilizers by improving timing and application techniques and applying the most efficient plant nutrition practices.
- Promote addition of organic matter in cultivated soils, as a way to reduce nitrogen losses and increase nutrient and water retention in the soil, and additionally sequester carbon in the soils; for example, in apple orchards in the United States, organic practices reduced nitrate runoff from farm soils (Kramer et al. 2006).
- Avoid bare soil. Studies show that the nitrate concentration in runoff from a field planted with row crops and left bare for some months a year is more than 20 times as much as that from one that's fully covered year-round with plants—be they pasture grasses or a succession of seasonal cover crops, such as red clover and white rye (Raloff 2004).

b. **Eliminate nutrient discharges from industry wastewaters,** by minimizing waste and securing a proper wastewater treatment.

c. **Secure collection and treatment of domestic wastes that remove nutrients,** especially in high-populated urban areas. Where water-borne infectious diseases are the primary health concern, primary and secondary sewage treatment must be the highest priority, in order to make drinking water safe from human pathogens. Where eutrophication and hypoxia in coastal waters are growing environmental and economic concerns, the need for tertiary treatment must also be recognized, to remove excess reactive nitrogen (UNEP and WHRC 2007).

d. **Ban phosphorus-based products** (e.g., detergents).

e. **Move towards stopping the burning of fossil fuels,** which contributes not only to climate change but also to nutrient loading, by atmospheric deposition.

2. Maximize natural nutrient retention by restoring vegetation along river courses, and on estuaries and wetlands. This would reduce nutrient and sediment losses from land-based activities (see more in Rabalais et al., 2007).

3. Fund research initiatives to understand the role of nutrients in HABs and dead zones and to document the historical changes in nutrient loading. In many regions, the specific sources of eutrophication and causes underlying HABs and dead zones are not well understood.

The preventing and mitigating of HABs needs a better knowledge base, using a quantification of nutrient inputs and modelling of future scenarios. For example, one of the most important questions in mitigating a particular dead zone is how much cut in nutrient inputs in a watershed must occur for its dead zone to shrink substantially. In the Gulf of Mexico, according to the National Oceanic and Atmospheric Administration (NOAA), nitrate releases would have to be cut nearly in half from current amounts to significantly shrink the annual Gulf dead zone to a fourth of its current size (a target set by the federal government in 2001: 5,000 km^2, from the current 20,000). But these cuts are not being realized and new market pressures, such as the growth in maize biofuel production, continue to increase nutrient loading in the Gulf.

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