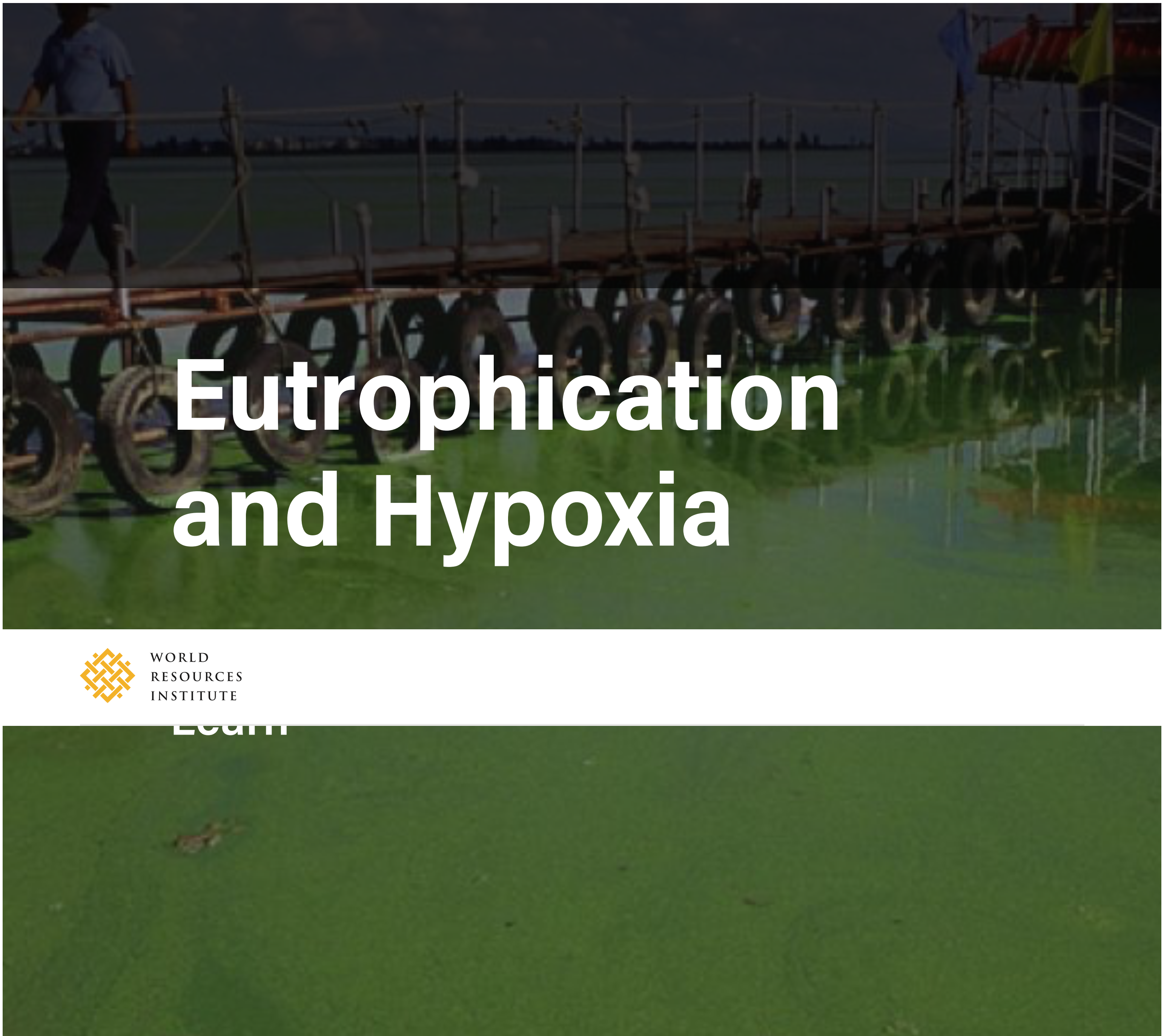

Eutrophication and Hypoxia

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Topic FRESHWATER

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About Eutrophication

Within the past 50 years, eutrophication — the over-enrichment of water by nutrients such as nitrogen phosphorus — has emerged as one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms, which among other things can destroy aquatic life in affected areas.

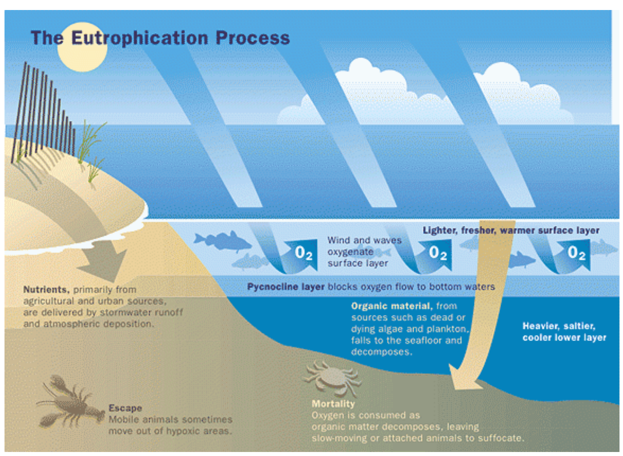

Fig 1. The eutrophication process and subsequent formation of sea-bottom hypoxia in coastal waters.

Image Credit: Pew Trusts

The rise in eutrophic and hypoxic events has been attributed to the rapid increase in intensive agricultural practices, industrial activities, and population growth which together have increased nitrogen and phosphorus flows in the environment. The Millenium Ecosystem Assessment (MA) found that human activities have resulted in the near doubling of nitrogen and tripling of phosphorus flows to the environment when compared to natural values.

Fig 2. This divided body of water shows the remarkable difference between mesotrophic (moderately enriched) (upper basin) and eutrophic water (lower basin).

Image Credit: Fisheries and Oceans Canada

Before nutrients—nitrogen in particular—are delivered to coastal ecosystems, they pass through a variety of terrestrial and freshwater ecosystems, causing other environmental problems such as freshwater quality impairments, acid rain, the formation of greenhouse gases, shifts in community food webs, and a loss of biodiversity.

Once nutrients reach coastal systems, they can trigger a number of responses within the ecosystem. The initial impacts of nutrient increases are the excessive growth of phytoplankton, microalgae (e.g., epiphytes and microphytes), and macroalgae (i.e., seaweed). These, in turn, can lead to other impacts such as: loss of subaquatic vegetation, change in species composition, coral reef damage, low dissolved oxygen, and the formation of dead zones (oxygen-depleted waters) that can lead to ecosystem collapse.

Impacts

Excess nutrients in coastal waters can

cause excessive growth of

Fig 1. Red tide in Xiamen, in China's Fujian Province, April 21, 2007. Red tides are nutrient-fueled blooms of phytoplankton that discolor water with their pigments. Several species are known to have toxic effects on marine life and pose a risk to human health through the consumption of exposed fish.

Image Credit: Gu Liuzhang / Asianewsphotos

phytoplankton, microalgae (i.e. epiphytes and microphytes), and macroalgae (i.e. seaweed).

In turn, the increase in phytoplankton and algae can lead to more severe secondary impacts such as:

- Loss of subaquatic vegetation as excessive phytoplankton, microalgae and macroalgae growth reduce light penetration.
- Change in species composition and biomass of the benthic (bottom-dwelling) aquatic community,

eventually leading to reduced species diversity and the dominance of gelatinous organisms such as jellyfish.

- Coral reef damage as increased nutrient levels favor algae growth over coral larvae. Coral growth is inhibited because the algae outcompetes coral larvae for available surfaces to grow.
- A shift in phytoplankton species composition, creating favorable conditions for the development of nuisance, toxic, or otherwise harmful algal blooms.
- Low dissolved oxygen and formation of hypoxic or "dead" zones (oxygen-depleted waters), which in turn can lead to ecosystem collapse.

The scientific community is increasing its knowledge of how eutrophication affects coastal ecosystems, yet the long-term implications of increased nutrient fluxes in our coastal waters are currently not entirely known or understood. We do know that eutrophication diminishes the ability of coastal ecosystems to provide valuable ecosystem services such as tourism, recreation, the provision of fish and shellfish for local communities, sportfishing, and commercial fisheries. In addition, eutrophication can lead to reductions in local and regional biodiversity.

Today nearly half of the world's population lives within 60 kilometers of the coast, with many communities relying directly on coastal ecosystems for their livelihoods. This means that a significant portion of the world's population is vulnerable to the effects of eutrophication in their local coastal ecosystems.

Fig 2. A series of phytoplankton blooms. A cyanobacterial (blue-green algae) in the Baltic Sea (upper left). Red tide bloom (dinoflagellate) in the Sea of Japan (upper right). Cyanobacterial bloom in the St John's River Estuary, Florida (lower left). Cyanobacteria-chlorophyte bloom in New Zealand (lower right).

Image Credit: Hans W. Pearl 2006

Two of the most acute and commonly recognized symptoms of eutrophication are harmful algal blooms and hypoxia.

Harmful Algal Blooms

Harmful algal blooms (Figures 1 and 2) can cause fish kills, human illness through shellfish poisoning, and death of marine mammals and shore birds. Harmful algal blooms are often referred to as “red tides” or “brown tides” because of the appearance of the water when these blooms occur. One red tide event, which occurred near Hong Kong in 1998, wiped out 90 percent of the entire stock of Hong Kong’s fish farms and resulted in an estimated economic loss of $40 million USD.

Hypoxia

Hypoxia, considered to be the most severe symptom of

Fig 3. A menhaden (Brevoortia sp.) fish kill in August 2003 was caused by severe hypoxic conditions in Greenwich Bay, part of Narragansett

Bay, Rhode Island, USA.

Image Credit: Chris Deacutis | IAN

eutrophication, has escalated dramatically over the past 50 years, increasing from about 10 documented cases in 1960 to at least 169 in 2007. Hypoxia occurs when algae and other organisms die, sink to the bottom, and are decomposed by bacteria, using the available dissolved oxygen. Salinity and temperature differences between surface and subsurface waters lead to stratification, limiting oxygen replenishment from surface waters and creating conditions that can lead to the formation of a hypoxic or "dead" zone. The formatioin of dead zones can lead to fish kills (Figure 3) and benthic mortality. Because benthic organisms are bottom dwelling and cannot easily flee low-oxygen zones, they are often the most severely impacted.

Sources

Where do nutrients come from?

Nutrient pollution released to freshwater and coastal areas comes from many diverse sources including agriculture, aquaculture, septic tanks, urban wastewater, urban stormwater runoff, industry, and fossil fuel combustion. Nutrients enter aquatic ecosystems via the air, surface water, or groundwater (Figure 1).

From region to region, there are significant variations in the relative importance of nutrient sources. For example, in the United States and the European Union, agricultural sources—commercial fertilizers and animal manure—are typically the primary sources of nutrient pollution in waterways, while urban wastewater is often a primary source of nutrients in coastal waterways of South America, Asia and Africa.

Agricultural Sources

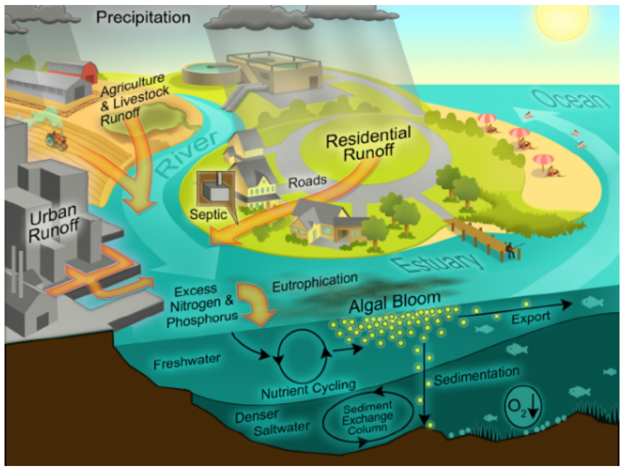

Fig 1. Schematic diagram of the different pathways of nutrient deposition into coastal waters and ensuing processes leading to eutrophication (algal blooms) and hypoxia.

Image Credit: Hans W. Paerl 2006

Agricultural nutrient sources include fertilizer leaching and runoff from agricultural fields; manure from CAFOs; and aquaculture operations.

Chemical fertilizers

Between 1960 and 1990, global use of synthetic nitrogen fertilizer increased more than sevenfold, while phosphorus use more than tripled. Studies have shown that fertilizers are often applied in excess of crop needs (MA 2005). The excess nutrients are lost through volatilization (when nitrogen vaporizes in the atmosphere in the form of ammonia), surface runoff (Figure 2), and leaching to groundwater. On average, about 20 percent of nitrogen fertilizer is lost through surface runoff or leaching into groundwater (MA 2005). Synthetic nitrogen fertilizer and nitrogen in manure that is spread on fields is also subject to volatilization. Under some conditions, up to 60 percent of the nitrogen applied to crops can be lost to the atmosphere by volatilization (University of Delaware Cooperative Extension 2009); more commonly, volatilization losses are 40 percent or less (MA 2005). A portion of the volatilized ammonia is redeposited in waterways through atmospheric deposition. Phosphorus, which binds to the soil, is generally lost through soil erosion from agricultural lands.

Manure

Fig 2. Nutrients and sediments entering the Mississipi River in the form of surface runoff. The latter is considered to be the main source of nitrogen into the Gulf of Mexico (Rabalais 2002)

Image Credit: Jerry Ting

The rapidly changing nature of raising livestock over the last century has also contributed to a sharp increase in nutrient levels. Animal production is intensifying, and as a result, more production is occurring further away from feedstock supplies, making it harder to spread the manure. The large quantity of manure produced by these operations is applied to land as fertilizer, stacked in the feedlot, or stored in lagoons. Frequently, an oversupply of manure means that it is applied to crops more than is necessary, further exacerbating nutrient runoff and leaching.

In China, meat production rose by 127

percent between 1990 and 2002 (FAO 2009a), but fewer than 10 percent of an estimated 14,000 intensive livestock operations have installed pollution controls (Ellis 2007). In the Black Sea region, one swine operation—which subsequently closed—had over 1 million pigs and generated sewage equivalent to a town of 5 million people (Mee 2006).

Aquaculture

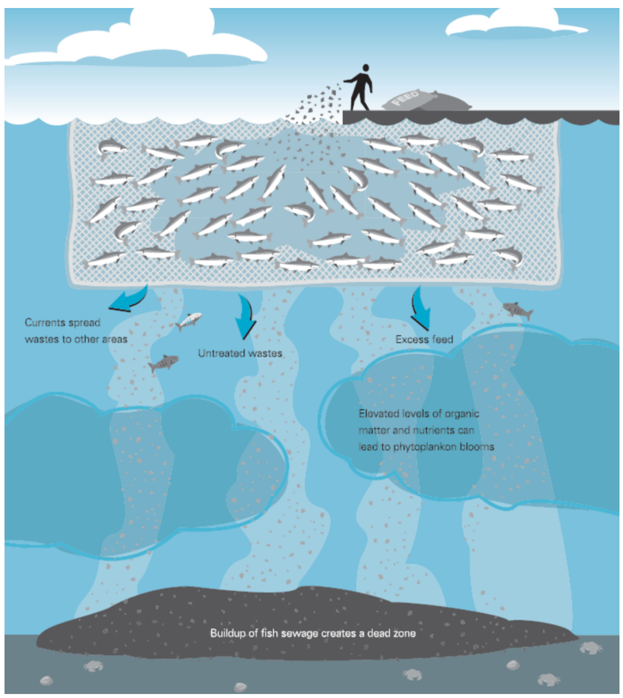

Fig 3. Diagram illustrating the mechanisms by which aquaculture can contribute to eutrophication and hypoxia.

Image Credit: Michael L. Webe | SeaWeb Aquaculture Clearing House

Aquaculture (fish farming) is another growing source of nutrient pollution. Annual aquaculture production worldwide increased by 600 percent in twenty years, from 8 million tons in 1985 to 48.2 million tons in 2005 (Figure 3). Today nearly 43 percent of all aquaculture production is within marine or brackish environments, with the remainder in freshwater lakes, streams, and man-made ponds (FAO 2007). Marine fish and shrimp farming often occur in net pens or cages situated in enclosed bays. These farms generate concentrated amounts of nitrogen and phosphorus from excrement, uneaten food, and other organic waste. If improperly managed, aquaculture operations can have severe impacts on aquatic ecosystems as nutrient wastes are discharged directly into the surrounding waters. For every ton of fish, aquaculture operations produce between 42 and 66 kilograms of nitrogen waste and between 7.2 and 10.5 kilograms of phosphorus waste (Strain and Hargrave 2005).

Urban and Industrial Sources

Municipal wastewater treatment plants and industrial wastewater discharges, nitrogen leaching from below-ground septic tanks, and stormwater runoff are some of the urban and industrial sources of nutrient pollution. Municipal and industrial sources are considered "point sources" of nutrient pollution because they discharge nutrients directly to surface waters or groundwater via a pipe or other discrete conveyance. They are typically the most controllable sources of nutrients and are often regulated in developed countries.

Table 1. Percentage of sewage treated in different regions worldwide.

Image Credit: Martinelli 2003 | Selman and Greenhalgh 2009

The most prevalent urban source of nutrient pollution is human sewage, though its importance varies by region and country. Sewage is estimated to contribute 12 percent of riverine nitrogen input in the United States, 25 percent in Western Europe, 33 percent in China, and 68 percent in the Republic of Korea (MA 2005). This variation is due, in large part, to differences in sewage treatment levels among countries (Table 1). In developing countries, fewer than 35 percent of cities have any form of sewage treatment (UNEP and WHRC 2007), and when sewage is treated, it is typically aimed at removing solids, not nutrients.

Households in developed countries often use septic systems when they are not connected to municipal wastewater treatment plants. Septic systems are designed to purify waste by leaching it through soils. They leach, on average, 14 kilograms of nitrogen per system per year—much of which reaches groundwater or nearby surface waters (Ann Arundel County Maryland DPW 2008). Stormwater runoff is another significant source of nutrients from urban areas. Rainfall events flush nutrients from residential lawns and impervious surfaces into nearby rivers and streams. In some cities, combined sewer overflow (CSO) systems worsen stormwater runoff problems. CSOs are designed to collect rainwater, domestic wastewater, and industrial wastewater in the same pipe. During heavy rain or snowmelt, wastewater volume can exceed the capacity of the CSO system, as well as that of the wastewater treatment plant receiving the flow. As a result, the excess wastewater, including raw sewage, is discharged directly into nearby streams and rivers. In the United States, over 772 cities had CSOs in 2007 (EPA 2007). For industrial sources of nutrient pollution, certain industries are larger sources than others. Pulp and paper mills, food and meat processing, agro-industries, and direct discharge of sewage from maritime vessels are some of the larger sources of industrial nutrient pollution.

Fossil Fuel Sources

When fossil fuels are burned, they

release nitrogen oxides (NOx) into the atmosphere. NOx contributes to the formation of smog and acid rain. NOx is redeposited to land and water through rain and snow (wet deposition), or can settle out of the air in a process called dry deposition. Coal-fired power plants and exhaust from cars, buses, and trucks are the primary sources of NOx. Fossil fuel combustion contributes approximately 22 teragrams of nitrogen pollution globally every year (Table 2), approximately one-fifth of the contribution of synthetic nitrogen fertilizers (MA 2005). In the Baltic Sea, atmospheric deposition, primarily from burning fossil fuels, accounts for 25

Fig 4. Smog from industry and vehicles originates in China and is blown over Yellow Sea towards Korea. Atmospheric deposition of NOx is a significant source of nitrogen to the Yellow Sea which suffers from severe symptoms of eutrophication.

Image Credit: NASA MODIS

percent of nitrogen inputs (HELCOM 2005). Similarly, in the Chesapeake Bay, atmospheric deposition accounts for 30 percent of all nitrogen inputs. In some areas, such as in the U.S. North Atlantic, atmospheric deposition of nitrogen can exceed riverine nitrogen inputs to coastal areas (Spokes and Jickells 2005).

Drivers

Complex and interrelated socioeconomic factors drive the increase in nutrient pollution, which is causing increased occurrences of eutrophication and hypoxia. Indirect drivers include population growth; economic growth in the developing world, which will impact consumer consumption; and the growth of intensive agriculture. Direct drivers of eutrophication include higher energy consumption, increased fertilizer consumption, and land-use change.

Indirect Drivers of Eutrophication

Population Growth

The global population is predicted to grow from 6.5 billion in 2005 to nearly 9.2 billion in 2050, with the majority of population growth occurring in less

Fig 1. Population growth, rising incomes and intensification of agriculture are ultimately driving activities which release more nutrients into the environment.

Image Credit: Ahron de Leeuw | Flickr developed countries (UNPD 2008). Of particular concern for the eutrophication predicament is population in coastal areas which is expected to grow from 1.2 billion people (c. 1990) to between 1.8 and 5.2 billion by the 2080s (Rabalais et al 2008). Population growth will increase the demand for food, land, energy and other natural resources, ultimately leading to greater agricultural production and increased burning of fossil fuels to heat homes, power cars, and fuel industry.

Economic Growth

Global per capita income is projected to double between 2002 and 2030, with the greatest income growth occurring in developing countries (Dargay et al. 2007). Per capita income of developing countries is expected to grow by 2.2 percent annually between 2002 and 2030. In developed countries, per capita income is forecast to grow approximately 1.5 percent annually (Dargay et al. 2007).

Increasing incomes will lead to changes in consumption patterns, such as different dietary choices, increasing energy use, and increasing consumption of consumer goods. Worldwide, dietary trends are moving toward greater meat consumption as a result of increased purchasing power, especially in the case of lower to middle income populations (FAO 2002). Between 1961 and 2002, the average worldwide per capita meat consumption rose by 87 percent, from an average per capita consumption of 21.2 kilograms per person to 39.7 kilograms per person (FAO 2009a). Between 2002 and 2030, meat consumption is expected to increase by 44 percent in the Middle East and North Africa region, 36 percent in East Asia, and 28 percent in Latin America and the Caribbean. South Asia, which currently has the lowest per capita meat consumption, is expected to double its meat consumption by 2030. Worldwide, per capita meat consumption is expected to increase by 14 percent by 2030, to an estimated average consumption of 45.3 kilograms of meat per person. When population growth is included, this rise equates to an estimated increase of 53 percent in total meat consumed worldwide.

Increased livestock production is expected to have significant implications for the severity of nutrient pollution worldwide. For example it is estimated that 80% of the nitrogen used in swine production is excreted as manure or lost to the environment during the production of animal feed (UNEP and WHRC 2007).

Direct Drivers of Eutrophication

Energy Consumption

Growing populations and expanding economies demand more energy. Total worldwide energy consumption rose by 33 percent between 1990 and 2005 (EIA 2008). Currently, more than 86 percent of the world's energy needs are being met by fossil fuel sources (coal, oil, and natural gas) (EIA

2008). Once combusted, fossil fuels discharge nitrogen oxides (NOx) into the atmosphere. While alternative energy sources such as solar, wind, and geothermal are available, the heavy reliance on fossil fuels is expected to continue in the short to medium term. Between 2005 and 2030, experts estimate that per capita energy consumption will increase by approximately 18 percent, while total global energy consumption will rise by 50 percent; the developing world is projected to account for the majority of increased energy consumption (EIA 2008). Fossil fuels are expected to continue meeting approximately 86 percent of global energy needs (EIA 2008).

Fertilizer Consumption

Growing populations, changing dietary trends that will increase

Fig 2. Graph illustrating fertilizer consumption since the 1960s as well as projected consumption until 2030. Here, fertilizer consumption includes nitrogen, phosphates, and potash.

Image Credit: Selman and Greenhalgh 2009 | Data from FAO 2009

the demand for meat, and expanding use of biofuels will necessitate increased agricultural production. As a result, fertilizer consumption is expected to increase 40 percent between 2002 and 2030 (Figure 2, base scenario) (FAO 2000). With genetic engineering to improve crop nutrient-use efficiency, this increase in fertilizer consumption is estimated to be only 17 percent over the same time period (Figure 2, nutrient efficiency scenario) (FAO 2000). The majority of the projected increase in global fertilizer consumption is attributed to the developing world where food production and adoption of intensive agricultural practices are expected to increase (FAO 2000).

Land-use Conversion and Agricultural Expansion

Tied to increased food production is

the conversion of land from perennial vegetation (plants that live for more than two years) to annual cropping. From 1995 to 2002, cropland has experienced a net increase globally of about 3 million hectares per year, with over 90 percent of the total cropland gains coming from forests (Holmgren 2006). Agriculture is also the single largest cause of wetland loss. Approximately 50 percent of the world's wetlands have been lost since the 1950s, the majority as a result of drainage for agricultural production (OECD/IUCN 1996). The FAO predicts that land-use conversion for agriculture will continue, but at a slower pace than in the past (FAO 2002). Natural landscapes such as

Fig 3. Globally, cropland has increased by about 3 million ha/year since 1995. The majority of cropland gains are from forest conversion. This photo shows slash-and-burn agriculture conversion in Costa Rica.

Image Credit: Arnold Paul | Wikimedia Commons forests and wetlands are important for capturing and cycling nutrients. Increasing land-use conversion reduces the ability of these landscapes to intercept nutrients and leads to greater nutrient losses to local waterways.

Other Drivers

Recent research suggests that eutrophication and subsequent hypoxia may be exacerbated by climate change and overfishing. Many of the factors driving the process of eutrophication are correlated and synergistic with those factors driving climate change and overfishing (e.g., growing demand for energy and increased food consumption linked to growing populations and economic growth). Below is a brief discussion of how these two factors are linked to eutrophication.

Climate Change

Climate Change has the potential to exacerbate expressions of eutrophication in water bodies and aquatic ecosystems that suffer from nutrient pollution, for example:

- Increased surface water temperatures linked to climate change could lead to stratification of the water column, thus preventing oxygenation of the colder bottom waters and possibly leading to hypoxic or anoxic conditions in systems already suffering from eutrophication.
- Warmer water temperatures (linked to climate change) combined with increased nutrient loads may be beneficial for certain harmful algal species and lead to increased frequency of harmful algal blooms. One example is the abundance of the dinoflagellate *Gambierdiscus Toxicus*, associated with fish poisoning, which has been positively correlated to increased surface water temperatures in tropical oceans caused by the meteorological phenomenon El Niño (Moore et al. 2008).
- Changes in precipitation patterns linked to climate change can also influence the expression of eutrophication. For instance, an

increase in precipitation may lead to changes in stratification patterns as more freshwater in the form of runoff (and associated desalinization) is discharged into coastal oceans, and will also translate into higher nutrient fluxes (Rabalais et al, 2008).

- Changing wind patterns linked to climate change could influence circulation and mixing in oceans and coastal zones. In turn this can influence stratification of the water column and lead to increasing or decreasing oxygen and nutrient levels in aquatic ecosystems (Rabalais et al, 2008). Changing wind patters may also affect existing patterns of upwelling and transport of nutrients in oceans.
- Accelerated sea level rise and coastal erosion linked to climate change poses a direct threat to a number of coastal ecosystems (IPCC 2007). These coastal features (e.g., wetlands, salt marshes) play a key role in the removal of excess nutrients entering coastal waters and their total effectiveness will be impaired by the reduction of their coastal coverage (Moss 2010).

Video: Climate Change, Eutrophication and Hypoxia in Oregon

Overfishing

Overfishing alters the food web and can help tip a system already suffering from eutrophication towards collapse. In a simple scenario, overfishing could lead to the removal of fish species that grazes on plankton. The removal of this species might in turn lead to a higher abundance of plankton, which, coupled with increased nutrient concentrations, can potentially lead to algal blooms and the subsequent formation of dead zones. For example, in the Black Sea, overfishing resulted in the removal of apex predators which triggered massive (and complex) changes in the aquatic food web, ultimately leading to the domination of species like jellyfish which favor ongoing eutrophic and hypoxic conditions (Daskalov et al. 2007). In the Black Sea, eutrophication, overfishing, introduction of exotic jellyfish species (e.g. Mnemiopsis leidyi) have led to algal blooms and formation of hypoxia (Arai 2001; Daskalov 2003).

Another example of where overfishing has been linked to increased expressions of eutrophication is the Chesapeake Bay. Excessive exploitation and destruction of oyster grounds in the Chesapeake Bay may be positively correlated to pronounced eutrophication and hypoxia events in the bay. Dense oyster beds once served as a filtering mechanism in the Chesapeake Bay. Oysters are filter feeders capable of controlling population dynamics in aquatic system by grazing prominently on phytoplankton thereby limiting blooms and improving water quality (Jackson et al. 2001; Lotze et al. 2006). The advent of harvesting through mechanical dredging in the

Chesapeake Bay (c. 1930s), led to a dramatic reduction of oyster reefs limiting their filtering ability and was likely one of the determining factors in the ensuing eutrophic and hypoxic conditions (Jackson et al. 2001).

Solutions

Finding solutions for mitigating eutrophication

Given the diversity of pathways, sources, and drivers of nutrient pollution, policies to address

Fig 1. Soldiers clear algae along the coastline of Qingdao, Shandong province, July 3, 2008. More than 10,000 people and 1,200 vessels were mobilized to tackle the huge algae bloom that threatened the Olympic sailing event in east China's Qingdao, out of the sea.

Image Credit: Ju Chuanjiang |

Asianewsphoto

eutrophication cannot be limited to traditional command-and-control approaches such as regulatory standards, nor can they be focused exclusively on a single sector such as wastewater treatment. Policymakers should look more broadly at agricultural, energy, land use, and public health policies and design these policies to mitigate nutrient pollution.

Types of policies to consider in a comprehensive nutrient reduction framework include:

- **education and outreach;**
- **research, monitoring, and evaluation;**
- **regulations;**
- **fiscal and economic incentives;**
- **ecosystem preservation and restoration;**
- **exploiting synergies with other environmental goals.**

Education and Outreach

Education and outreach include shaping values through environmental education in schools, building knowledge and skills through outreach to communities and industry, and raising public awareness and support for political action through targeted communication campaigns.

Environmental Education

Fig. 1. Use of quadrat to determine algal mat cover on a rocky shore as part of a training session of the Long-term Monitoring Program and Experimental Training for Students (LIMPETS). This program aims to educate students and teachers in several aspects of coastal monitoring in order to promote the conservation of marine ecosystems.

Image credit: LIMPETS

Environmental education helps shape values and raise environmental awareness from an early age. It focuses on teaching the inherent value of the environment; the interconnectedness of environment, economy, culture, and health; and how human actions affect the environment. Environmental education may be the most important avenue for addressing the indirect drivers of eutrophication. It informs people about how the choices they make ultimately impact the environment and can lead to changes in individual behaviors and lifestyles that reduce nutrient pollution.

While some countries incorporate environmental education into primary and secondary school curricula, many do not. For instance, environmental education is lacking in many former Communist countries in the Black Sea region; as a result, social attitudes reflect the low value placed on the environment (McQuatters-Gallop and Mee 2007). Despite efforts by nongovernmental organizations (NGOs) in countries such as Romania, Russia, Bulgaria, Turkey, Georgia, and Ukraine, environmental education is still not widely incorporated in school curriculums.

In contrast, environmental education is

an important component of efforts to restore the Chesapeake Bay in the United States. As part of the Chesapeake 2000 agreement, states within the Chesapeake Bay drainage area agreed to incorporate Chesapeake Bay issues into school curriculums. For example, Chesapeake 2000 stipulates that every student residing in the Chesapeake Bay region should have a "meaningful Chesapeake Bay and/or stream experience" before graduation from high school (Chesapeake Bay Program 2001).

Public Awareness

Raising awareness can change public perceptions of

Fig 2. Watershed signs like these are meant to educate the public about the Chesapeake Bay restoration efforts. They highlight the concept of a watershed and demonstrate that even those who may not be located in close proximity to the Bay can be part of the restoration effort.

eutrophication, alter individual

behavior, and pressure governments to take steps to mitigate eutrophication. The first step in raising awareness is to pose the question: “Why does it matter to me?” Relevant and reliable data and research are needed to underpin and create compelling messages. While messages should be based on sound science, they should be expressed in terms and concepts that are easily understood by the public.

In the Chesapeake Bay, for instance, public awareness efforts include iconic images of crabs and slogans such as “Save the Bay” and “Treasure the Chesapeake.” Other efforts in the Chesapeake Bay include marking storm drains that carry runoff into the Chesapeake Bay or its tributaries (in an effort to prevent dumping); marking watershed boundaries with road signs; offering license plates with a Chesapeake Bay theme; implementing subway advertising campaigns and educational displays; and garnering newspaper and television media coverage of the issue.

Outreach and Technical Assistance

Outreach activities and technical assistance are important for building the knowledge and skills required for individuals and industries to begin addressing nutrient pollution. For example, outreach to the agricultural community can educate farmers on nutrient-related pollution issues and farm-level management practices that mitigate nutrient losses. In the United States, the U.S. Department of Agriculture provides support to educate farmers on conservation practices and provides technical assistance to farmers implementing

Fig 3. A member of the U.S Department of Agriculture discusses manure management with dairy farmers in Stanislaus County, CA. Technical assistance and education are important mechanisms in limiting nutrient pollution in waterways.

Image credit: Lynn Betts | U.S Department of Agriculture nutrient-reducing management practices, such as appropriate manure handling and fertilizer application rates. As with most policies, the success of outreach and technical assistance will vary depending on the effectiveness of the outreach strategy, suitability of the technology or practice being promoted to meet community needs, ease of adoption, and willingness to change on the part of the targeted community.

Fiscal & Economic Incentives

Types of economic and fiscal incentives that can be used to incentivise reductions in nutrient pollution include ecotaxes, incentive payments/subsidies, ecolabeling, and environmental markets (adapted from Sands 2003. These mechanisms are meant to complement or avoid regulatory approaches. These policies are described in more detail below.

Ecotaxes

Ecotaxes, also known as green fees

and taxes, are meant to create "full cost accounting" of economic activities by using fiscal policies to internalize negative externalities. Some examples of green fees and taxes that can be used in the context of mitigating eutrophication include:

Image Credit: F. Lamiot | Wikimedia Commons

- *Polluter-pays tax*. A polluter-pays tax provides economic incentives for ecologically sustainable activities—or, conversely, disincentives for activities that are not ecologically sustainable. For example, Denmark's wastewater tax, imposed on point sources (industry and wastewater treatment plants), levies a tax on every unit of nitrogen, phosphorus, and biological oxygen demand (BOD) discharged in wastewater (EcoTech 2001). Similarly, the Netherlands employs a fee system for agriculture that levies fines on farms with nitrogen and phosphorus in excess of their approved nutrient budget (Hoffmann and Boyd 2006).

- *Dedicated environmental tax*. Governments can impose taxes and fees directly on a sector or population, and then use the revenue to fund nutrient reducing activities or technologies. For example, in Maryland (U.S.) an annual fee commonly called the "flush tax" is levied on every household and business in the state via their water and sewer bill. The revenues from this tax are used to upgrade wastewater treatment plants with nutrient removal technologies and add nitrogen-removing capability to septic systems.
- *Taxes on technologies/products/inputs with negative environmental impacts*. Placing a tax on technologies, products or inputs that are associated with negative externalities creates a price signal aimed to reduce demand for the taxed good. A fertilizer tax is an example of an input tax. The effectiveness of this kind of tax is dependent on the elasticity of demand and availability of substitutes.

Incentives and subsidies

Incentive payments, subsidies, tax credits, and low-interest loan programs are economic instruments used to encourage adoption of desirable practices. Agricultural conservation subsidies in the United States are used to encourage farmers to implement best management practices that will reduce nutrient and soil loss on farms. In Pennsylvania, the Resource Enhancement and Protection Program provides a tax credit for farmers who implement best management practices that improve water quality. Pennsylvania estimated that over a two-year period (2007-2008) the program reduced nitrogen pollution by 162,176 pounds and phosphorus runoff by 14,939 pounds (Pennsylvania Department of Agriculture 2009). The U.S. Clean Water State Revolving Fund (CWSRF) loan program currently offers $5 billion annually in low-interest loans to municipalities and wastewater treatment plants to help fund water quality protection projects for wastewater treatment and watershed management (EPA 2009a). Since inception, the CWSRF program has spent more than $2.9 billion to control pollution from nonpoint sources and for estuary protection (EPA 2009a).

The effectiveness of incentive payments improves when performance-based approaches are used [(Guiling et al. 2006)]/publication/paying-environmental-performance-investing-farmers-and-environment). Performance-based approaches use incentive payments based on actual environmental outcomes rather than paying for actions and implementation of practices. Performance-based approaches can include incentive payments based on quantitative estimates of environmental benefits as well as mechanisms such as reverse auctions. Reverse auctions have been used in the United States and Australia to cost-effectively allocate money to landowners who reduce nutrient losses (Eigenraam 2005; Selman et al. 2007; Selman et al. 2008). In reverse auctions, multiple sellers (e.g., landowners) compete to supply a single buyer (e.g., the government) with a specified good or service, enabling the buyer to locate the most competitive sellers. In an environmental context, reverse auctions can be used to maximize environmental benefits given a limited funding budget.

Ecolabel

Ecolabeling is a voluntary method of certifying products that are produced in a way that is environmentally preferable to other products in the same product/service category based on life cycle considerations. Ecolabeling is meant to

The European Union's Ecolabel is a voluntary scheme established in 1992 to encourage businesses to market products and services that are kinder to the environment.

create consumer preference for "green" products and thus generate a financial return to the supplier of the certified product in the form of increased revenues. Ecolabeling of agricultural products can provide incentives for farmers who wish to certify their products and adopt sustainable agricultural practices.

Environmental Markets

Environmental markets, including regulatory and voluntary markets, use a market to provide price signals for environmental goods and are meant to align behavior with environmental goals.

Regulatory markets are meant to provide flexibility to regulated sources, thereby reducing the financial burden of regulatory compliance with limits or caps on nutrient emissions. For example, regulatory water quality trading markets for nutrients exist in the United States, Canada, and New Zealand (Selman et al. 2009) and are designed to both minimize the costs of complying with effluent nutrient caps and offset new nutrient discharges from new and expanding sources. One example of an active water quality trading program is the Long Island Sound Nitrogen Credit Exchange in Connecticut. Connecticut allows wastewater treatment plants capped under the Long Island Sound TMDL to meet their nitrogen discharge limits by upgrading their facility or by purchasing nitrogen offsets from another facility that is operating below its discharge limit. Another example is in New Zealand. Farmers in Lake Taupo are able to purchase additional nitrogen discharge allowances from other farms or implement management practices to meet their regulatory obligations or expand their production.

Conversely, voluntary markets are not driven by regulation, but by the value placed on the environmental good or service by the buyer. Voluntary markets generally follow the “payment for ecosystem services” model, where buyers (motivated by altruism or selfinterest) are willing to pay landowners to maintain or enhance ecosystem services (e.g., water purification, flood control, carbon sequestration). For example, in the Chesapeake Bay, a consortium of NGOs has established a voluntary nutrient market called the Chesapeake Fund. Individuals and companies that wish to offset their "nutrient footprint" can purchase nutrient offsets from the Fund. In turn, the Chesapeake Fund uses these revenues to pay farmers in the watershed to implement nutrient-reducing best management practices.

Regulations

Regulatory approaches, also referred to as "command and control" approaches, represent one of the most straightforward approaches to controlling pollution, including nutrients. Environmental regulations can take two general forms: standards and emissions/effluent caps or limits. While standards specify certain technologies, practices, or processes that must be implemented, regulatory caps set a level of acceptable pollution, but do not dictate how this level is to be achieved. The two regulatory approaches are described in more detail below.

Standards

Standards prescribe particular technologies, practices, or processes that are meant to achieve a specific outcome. Standards might also impose limits on pollution or activities in order to protect the environment. Examples of regulatory standards include:

Fig 1. The European Union Nitrate Directive requires that areas designated as Sensitive Farming Areas (SFAs) must have manure application standards that limit application rates to no more than 170 kg/ha/yr.

Image Credit: Photo Credit: Bob Nichols | U.S Department of Agriculture

- *Environmental quality standards* restrict pollution or activities in order to protect the resource or the environment. For example, harvest limits on oysters in the Chesapeake Bay are being used to lessen pressures on the oyster population in the Bay. Oysters provide a valuable ecosystem service by consuming algae and other waterborne nutrients.

- *Product/manufacturing standards* establish levels of pollutants that cannot be exceeded in the manufacture of a product or emissions from a product. Product standards might also specify the properties or specifications for product design. For example, U.S. law includes nitrogen oxides (NOx) emission standards for vehicles sold in the United States. Vehicles must be designed in such a way as to not exceed maximum NOx emission thresholds.

Fig 2. A trickling filter bed water treatment system. This simple wastewater treatment system consists of spraying wastewater into a corrugated medium where a layer of microorganisms (biofilm) exists. As the water traverses through the medium, organic particles are attached to the biofilm eliminating organic residues. Small filters are recommended for places lacking municipal sewage treatment systems.Image Credit: Hugh Venables | Geograph.org.uk

- *Process/design standards* include installation and design standards as well as operating standards. Installation and design standards set requirements that must be met in the design and construction of various installations. Operating standards determine requirements that must be met during the operation of an installation. In Maryland, the Stormwater Management Act of 2007 provides design standards for developers that require new developments to manage stormwater runoff and use design practices with low environmental impact. Mitigating stormwater runoff helps prevent nutrient losses through runoff.
- *Technology/practice standards* include prescriptions for the type of technology that must be used or the practices that must be

implemented to achieve the desired environmental outcome. For example, in Maryland, all major treatment plants are required to upgrade to enhanced nitrogen removal treatment technologies. Enhanced nutrient removal is the current state-of-the-art technology for nutrient removal in wastewater treatment plants. It is capable of reducing nitrogen concentrations in wastewater discharge to 3 mg/l and phosphorus concentrations to 0.3 mg/l. In contrast, biological nutrient removal technology can only reduce nitrogen discharges to 8 mg/l and phosphorus discharges to 3 mg/l (Saffouri 2005). (Typology of regulatory standards is adapted from Sands 2003.)

Effluent/Emissions Limits and Caps

Effluent/emissions limits and caps include limits on the amount of allowable pollution discharge that can be emitted to the air or water. Unlike standards, regulatory caps do not prescribe the implementation of specific technologies or practices;

rather, they place limits on the amount of pollution (e.g., nutrients) that can be released into the environment. The regulated source is generally given flexibility on how this cap is met.

In some cases, regulatory caps are placed at the watershed level, or at some other aggregate level. In the case of watershed caps, the amount of nitrogen or phosphorus leaving a watershed is capped and individual sources of nutrient pollution within the watershed must ensure that this cap is met. For example, under the U.S. Clean Water Act, states must develop and implement a total maximum daily load (TMDL) for water bodies that are impaired by excess nutrients. The TMDL sets a watershed cap and identifies the nutrient sources and reductions required from each source to comply with the TMDL. For instance, in the Long Island Sound (Connecticut and New York, U.S.) a TMDL was developed for nitrogen that calls for the removal of 24 thousand tons of nitrogen by 2014. The TMDL identified that 80 percent of the nitrogen load was from wastewater treatment plants, with the remainder of the load coming from urban stormwater runoff and atmospheric sources originating outside of the watershed. The implementation of the TMDL resulted in effluent nitrogen limits for all wastewater treatment plants in the basin, effectively requiring a 64 percent reduction in nitrogen discharges from regulated facilities (Connecticut Department of Environmental Protection 2001).

Research & Monitoring

Research, monitoring, and evaluation activities are essential for

Fig 1. This picture shows a Secchi disk in use. The black-and-white disk is the most common tool used to identify the transparency of water bodies which is correlated to phytoplankton abundance.

Image Credit: Biological Sciences Department Kent State University

characterizing the nature of the eutrophication problem, providing information and support tools to inform policies, and establishing effective measures for managing and reducing nutrient losses.

Examples of important research, tools, and monitoring efforts include:

- Time series monitoring data to evaluate long-term trends and provide a better understanding of the drivers, sources, and impacts of eutrophication;
- Watershed models that assess nutrient fate and transport within watersheds, inform management scenarios, provide watershed analysis, and evaluate progress toward environmental goals;
- Nutrient source information such as location of sources, land use information, animal numbers, and population information;
- Watershed boundaries, location of waterways, and groundwater flows;

and

- Nutrient budgets—watershed analyses that identify the amount and sources of nutrients entering waterways—to identify the appropriate actions to reduce nutrient losses. Nutrient budgets form the basis of nutrient reduction strategies and identify those actions needed to meet reduction targets for agricultural, urban, and point sources.

In addition to the need for adequate data about eutrophication and its effects, it is important to support research and development of technologies, processes, and practices for mitigating and controlling nutrient losses. Examples of critical research ares include research on measures that can be undertaken on farms to reduce nutrient losses, research and development of nutrient efficient crop varieties, and development of technologies and processes that can be used to reduce nutrient pollution.

Restoration & Protection of Ecosystems

Preserving and restoring riparian forests, wetlands, mangroves, and open areas can mitigate nutrient pollution by creating and maintaining natural nutrient sinks. These policies can take many forms, including:

Fig 1. Volunteers plant sea grass as part of a restoration effort in the Patuxent River, Chesapeake Bay. Sea grass beds restoration is beneficial given that it is a key component of aquatic ecosystems due to its role in nutrient absorption and recycling.

Image Credit: John Verrico | U.S. Navy

- *Protected areas*. Establishing protected areas through legal measures can serve to protect and preserve critical ecosystems. In 1998, 6,264 km2 of the Danube Delta (Romania and Ukraine) were protected as part of the UNESCO Man and Biosphere program. The Danube Delta lies on the coast of the Black Sea and is Europe's largest wetland and reed bed. It is a critical ecosystem for capturing and cycling nutrients (UNESCO 2007).
- *Land purchases and establishment*

of conservation easements. Public and private purchases of ecologically valuable land as well as establishment of conservation easements (i.e., the purchase of development rights) can help reduce nutrient pollution by protecting ecosystems that capture and cycle nutrients.

For example, the Worcester Land Protection Partnership is a partnership between the city of Worcester (Massachusetts, U.S.) and the Trust for Public Land, a nonprofit land conservation organization, aimed at identifying and acquiring priority watershed land for the purpose of

Fig 2. Lamesley Wetlands is an experimental sewage treatment system in Northumbria, UK. Here, reed beds are simultaneously efficient in treating phosphate rich wastewater effluents and water from mine workings. The experimental system is efficient, inexpensive and provides habitat for a number of species.

Image Credit: Chrish Heaton | Geograph.org.uk improving and maintaining water quality within the rivers and reservoirs (Trust for Public Land 2008).

- *Habitat restoration*. Often the aquatic ecosystems most severely impacted by eutrophication are the ones that have been already degraded due to other causes (Mee 2006). Human pressures on fish stocks, shoreline erosion, and loss of submerged aquatic vegetation make ecosystems more vulnerable to the impacts of eutrophication. In the United States, Maryland and Virginia have both funded restoration efforts aimed at restoring submerged aquatic vegetation and replenishing oyster beds in the Chesapeake Bay.

Capitalize on Synergies

Nutrient pollution and eutrophication are strongly linked with other global environmental issues like climate change, air pollution and acid rain. Policymakers should exploit the linkages between eutrophication and other local, regional, and global environmental issues and identify those policies that minimize tradeoffs and maximize environmental benefits. Combustion of fossil fuels, for example, emits nitrogen oxides (NOx), which can be a significant source of nutrient pollution to aquatic ecosystems through the process of atmospheric deposition (Spokes and Jickells 2005).

NOx also contributes to other

Fig 1. Forested buffers along streams filter nutrients and sediments before they reach surface waters. These buffers also create habitat, stabilize streambanks and sequester carbon.

Image Credit: Peggy Grebb | U.S. Department of Agriculture

environmental problems such as acid rain and smog. In addition to NOx, combustion of fossil fuels also releases significant amounts of carbon dioxide into the atmosphere—the gas that is primarily responsible for climate change. Policies aimed at reducing combustion of fossil fuels through energy conservation, energy efficiency, and promotion of alternative energy thus have multiple environmental and public health benefits (Moomaw 2002).

Another area with considerable environmental synergies is agricultural policy (Greenhalgh and Sauer 2003). Agricultural policies aimed at providing incentives to farmers to install and implement improved nutrient management on their farms often have several environmental benefits beyond improved water quality. Best management practices that reduce nutrient runoff can also improve wildlife habitat, reduce soil erosion, sequester carbon dioxide, and reduce emissions of nitrous oxide, a greenhouse gas with a warming potential 281 times greater than carbon dioxide (EPA 2009b).

In contrast, policies aimed at mitigating

Fig 2. Compost production from organic waste in Batam, Indonesia. This is part of a sustainable development scheme aiming to limit land-based pollution in the South China Sea. Farmers collect and treat organic wastes to produce fertilizer which can then be used on their crops and as an additional source of income.

Image Credit: UNEP 2007

eutrophication that are narrowly focused on regulating wastewater treatment plants have very few environmental co-benefits. In fact, many of the advanced nutrient removal technologies that would be installed by wastewater treatment plants use significantly more energy—which, depending on the method of energy generation, may lead to greater emissions of NOx and carbon dioxide—and possibly emit a significant portion of the captured nitrogen into the atmosphere through volatilization (Foley et al 2007). While primary and secondary treatment of sewage discharges from wastewater treatment plants is important for human health, it is necessary for policymakers to weigh tradeoffs of advanced tertiary treatments and ensure that the selected policies adequately consider the various sectors, sources of nutrient pollution, and other environmental issues.