WRI POLICY NOTE

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WATER QUALITY: EUTROPHICATION AND HYPOXIA No. 2

Eutrophication: Sources and Drivers of Nutrient Pollution

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Key Findings

Nutrient over-enrichment of freshwater and coastal ecosystems, or eutrophication, is a rapidly growing environmental crisis. Worldwide, the number of coastal areas impacted by eutrophication stands at over 500. In coastal areas, occurrences of dead zones, which are caused by eutrophic conditions, have increased from 10 documented cases in 1960 to 405 documented cases in 2008. In addition, many of the world's freshwater lakes, streams, and reservoirs suffer from eutrophication; in the United States, eutrophication is thought to be the primary cause of freshwater impairment. Many of our largest freshwater lakes are entrophic, including Lake Erie (United States), Lake Victoria (Tanzania/Uganda/Kenya), and Tai Lake (China).

The increase in eutrophication is the result of human activities. Major sources of nutrients to freshwater and coastal ecosystems include wastewater, agriculture, and atmospheric deposition of nitrogen from burning fossil fuels.

The drivers of eutrophication are expected to increase for the foreseeable future. Specifically:

- World population will continue to grow, reaching an estimated 9.2 billion by 2050, which will increase pressures on the productive capacity of agriculture and industry.
- Intensive agriculture and land use conversion—for crops, livestock, and aquaculture—will increase, especially in the developing world. In addition to population growth, intensification is driven by changing dietary patterns. For example, over the period from 2002 to 2030, global meat consumption is expected to increase by 54 percent.
- Energy consumption is expected to grow 50 percent from 2005 to 2030. Fossil fuels, which release nitrogen oxides (NO_x) into the environment when burned, will continue to be the dominant fuel source in this century.

As a result of these increasing global trends in population growth, energy use, and agricultural production, we expect that coastal and freshwater systems impacted by eutrophication and hypoxia will continue to increase, especially in the developing world.

Human-induced eutrophication, or nutrient over-enrichment, is a rapidly growing environmental crisis in freshwater and marine systems worldwide. Nutrients that cause eutrophication include nitrogen and phosphorus. While nitrogen and phosphorus are critical to biological processes in aquatic ecosystems, increased runoff of these nutrients to aquatic ecosystems from land-based sources results in increased biomass production, upsetting the natural balance of these ecosystems. Eutrophication can ultimately result in harmful algal blooms, the formation of hypoxic[1] or "dead" zones, and ecosystem collapse. Today, over 500 coastal areas have been identified as suffering from the effects of eutrophication; of these, 405 have also been documented as hypoxic (compiled from Selman et al. 2008 and Diaz and Rosenberg 2008). In freshwater systems, phosphorus is often the main cause of impairment, while nitrogen is generally linked with the impairment of coastal systems. In addition to contributing to eutrophication, nitrogen pollution also contributes to other environmental problems such as acid rain, climate change, and local air pollution. Nitrous oxide (N_2O)—a nitrogen-based greenhouse gas that contributes to climate change—is linked primarily to agriculture and is 310 times more powerful than carbon dioxide. Nitrogen oxides (NO_x) are another family of nitrogen-based gases that are released into the atmosphere from fossil fuel combustion. NO_x is highly reactive and contributes to the formation of smog—which can have significant impacts on human health—and acid rain.

This policy note provides a snapshot of the sources of nutrient pollution and the corresponding socioeconomic drivers that are increasing nutrient levels in our waterways. It complements *Eutrophication and Hypoxia in Coastal Areas: A Global Assessment of the State of Knowledge* (Selman et al. 2008), a previously released publication on the extent of eutrophication worldwide.

Where Do Nutrients Come From?

Sources of nutrient pollution released to freshwater and coastal areas are diverse, and include 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 (Table 1). Among regions, there are significant variations in the relative importance of nutrient sources that contribute to eutrophication of local and coastal waterbodies. For example, in the United States and the European Union, agricultural sources—commercial fertilizers and animal manure—are typically the primary sources of nutrient impairment in waterways, while urban wastewater is the primary source in Asia and Africa.

TABLE 1. Primary Sources and Pathways of Nutrients

	Pathways		
Sources	Air	Surface Water	Groundwater
Sewage treatment plants		✔	
Industry	✔	✔	
Septic systems		✔	✔
Urban stormwater runoff		✔	
Agricultural fertilizers	✔	✔	✔
Livestock operations	✔	✔	✔
Aquaculture		✔	
Fossil fuel combustion	✔		

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 losses. 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 2. Percent of Sewage Treated by Region

Region	Percent of Sewage Treated
North America	90
Europe	66
Asia	35
Latin America & Caribbean	14
Africa	<1

Source: Martinelli 2003 as cited in MA 2005

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 2). 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 primary treatment aimed at removing solids, not nutrients. Where households are not connected to municipal wastewater treatment plants, septic systems are often used in developed countries. 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 then conveys into groundwater or nearby surface waters (Anne 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.

Agricultural Sources

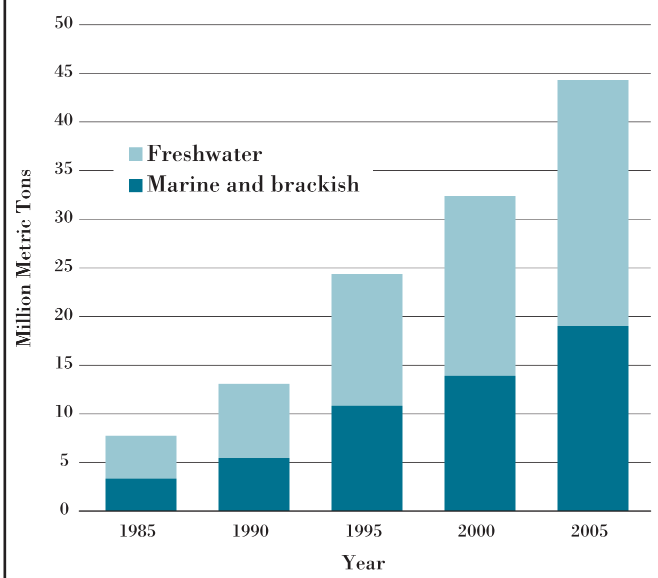
Fertilizer leaching, runoff from agricultural fields, manure from concentrated livestock operations, and aquaculture are the largest agricultural nutrient sources. Between 1960 and 1990, global use of synthetic nitrogen fertilizer increased more than sevenfold, while phosphorus use more than tripled, with chemical fertilizers often being applied in excess of crop needs (MA 2005). The excess nutrients are lost through volatilization, surface runoff, 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. Volatilization is where nitrogen in the form of ammonia is lost to the atmosphere. 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 sheet and rill erosion from agricultural lands.

The rapidly changing nature of raising livestock has also contributed to a sharp increase in nutrient fluxes over the last century. Animal production is intensifying, with increasingly more production occurring further away from feedstock supplies. The large quantity of manure produced by these operations is applied to land as fertilizer, stacked in the feedlot, or stored in lagoons. Frequently, the rate and timing of land application of manure is dictated by the volume and availability of manure and not by crop needs. This leads to ill-timed or overapplication of manure, 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 is another growing source of nutrient pollution. Annual aquaculture production worldwide increased by 600 percent, from 8 million tons in 1985 to 48.2 million tons in 2005 (Figure 1). 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).

FIGURE 1 The Global Increase in Aquaculture Production



Source: FAO 2007

Fossil Fuel Sources

When fossil fuels are burned, they release nitrogen oxides (NO_x) into the atmosphere. NO_x contributes to the formation of smog and acid rain. NO_x 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 NO_x. Fossil fuel combustion contributes approximately 22 teragrams[2] of nitrogen pollution globally every year (Table 3), 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 percent of nitrogen inputs (HELCOM 2005). Similarly, in the Chesapeake Bay, atmospheric deposition accounts for 30 percent of all nitrogen inputs.[3] 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).

TABLE 3. Global Nitrogen Oxide Emissions, 2000

Region	NO_x Emissions (1,000 metric tons)
Asia (excluding Middle East)	37,722
Central America & Caribbean	3,881
Europe	25,536
Middle East & North Africa	7,572
North America	21,839
Oceania	3,381
South America	11,748
Sub-Saharan Africa	14,926
TOTAL	126,605

Source: WRI 2009

What Drives the Increasing Eutrophication Trends?

Complex and interrelated socioeconomic factors drive the increase in nutrient pollution, which is causing increased occurrences of eutrophication. 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 developed countries (UNPD 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).

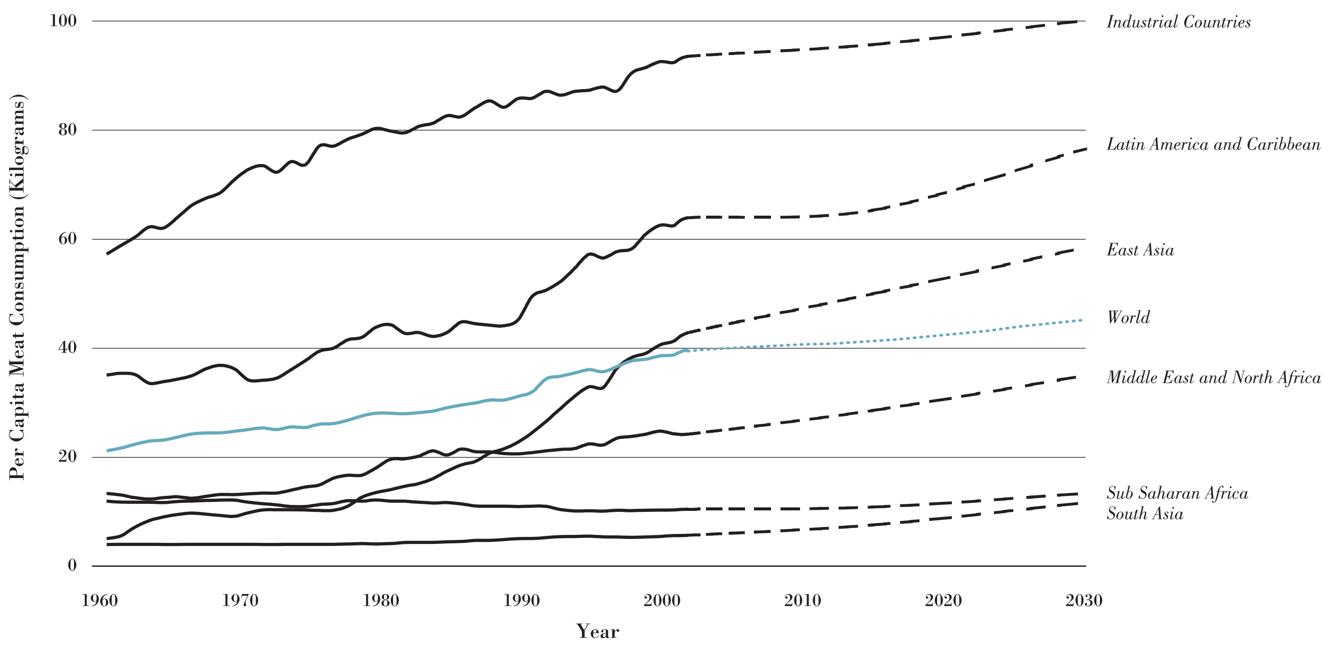
Increasing incomes will lead to changes in consumption patterns, such as different dietary choices, increasing energy use, and increasing consumption of consumer goods. For example, worldwide, dietary trends are moving toward greater meat consumption as a result of increased purchasing power, especially 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 (Figure 2). When population growth is included, this rise equates to an estimated increase of 53 percent in total meat consumed worldwide.

The increased livestock production that will be necessary to meet growing global demand for meat is expected to have significant implications for for the severity of nutrient pollution worldwide. For example it is estimated that only 20 percent of the nitrogen used in swine production is actually consumed by humans; the remainder is excreted as manure or lost to the environment during the production of animal feed (UNEP and WHRC 2007). In contrast, one study of the Mississippi River Basin estimated that if feed cultivation for meat production were switched to crops that would support a lacto-ovo-vegetarian diet, nitrate exports to the Gulf of Mexico would decrease by 50 percent (Donner 2006).

Agricultural Intensification

In the past 70 years, the way in which we grow food has changed dramatically. The "Green Revolution," which began in the 1940s, made significant advances in agricultural production, introducing the widespread use of agrochemicals such as synthetic fertilizers and pesticides to improve crop yields. These chemicals and modern machinery allowed the intensification of agriculture. While the intensification of agriculture has led to economies of scale and improved food security, it has also led to significant unintended environmental impacts such as nutrient pollution. While agriculture in developed countries is already highly intensive, we expect to see greater agricultural intensification in developing countries in the coming decades.

FIGURE 2 | **Per Capita Meat Consumption**



Source: Historical data from FAO 2009a, projected data from FAO 2002

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 NO_x 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).

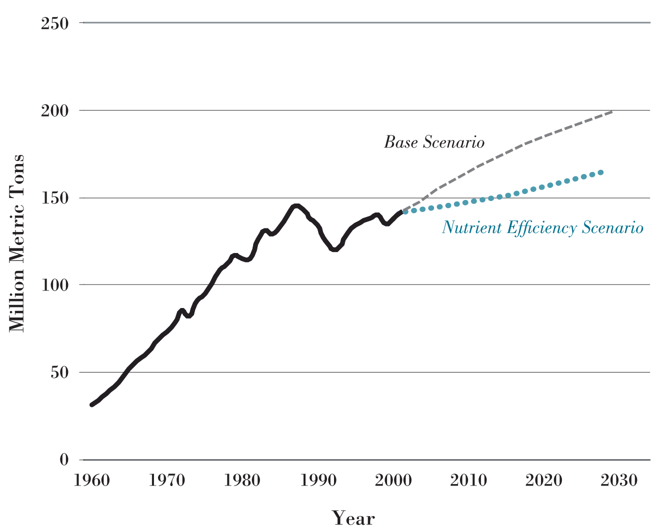
Fertilizer Consumption

Growing populations, changing dietary trends that are increasing the demand for meat, and the 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 3, base scenario) (FAO 2000). With genetic engineering to improve crop nutrient-use efficiency, this increase in fertilizer use is estimated to be only 17 percent over the same time period (Figure 3, 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

Tied to increased food production is the conversion of land from perennial vegetation 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 of wetland loss occurred 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 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.

FIGURE 3 **Projected Increase in Global Fertilizer Consumption***



Source: Historical data from FAO 2009b, projected data from FAO 200.
* Fertilizer consumption includes nitrogen (N), phosphates (P_2O_5) and potash (K_2O).

Conclusions and Next Steps

Population growth is driving increased demand for energy and food. This increase will further exacerbate nutrient losses from urban, industrial, and agricultural sources as well as those from combustion of fossil fuels. As a result, we expect to see increasing numbers of coastal and freshwater ecosystems impacted by eutrophication and hypoxia in the future. It is likely that eutrophication will increase most rapidly in the developing world, where population, meat consumption, and energy consumption are expected to increase more rapidly than in developed countries.

At its core, eutrophication is a byproduct of unsustainable agricultural production and energy use. Because the pathways, sources, and drivers of nutrient pollution are varied and diverse, the policies that address eutrophication cannot be limited to traditional environmental regulations. Instead, policymakers must look more broadly at agricultural, energy, land use, and public health policies and find ways that these policies can be designed to mitigate nutrient pollution. Finally, there are strong linkages between the sources and drivers of eutrophication and those of climate change and other critical environmental issues like air pollution and acid rain. Developing a more robust understanding of the sources and drivers of eutrophication will allow policymakers to identify the linkages between eutrophication and other local, regional, and global environmental issues and identify those policies that minimize tradeoffs and maximize environmental benefits. A forthcoming publication in this series will focus on the types of institutions, actions, and policies that are critical for addressing eutrophication.

Notes

1. Hypoxia generally occurs when the dissolved oxygen concentration of water is 2.0 milligrams per liter or less.
2. 1 teragram (Tg) is equal to 1 million metric tons
3. Source: Personal communication with Lewis Linker at the Chesapeake Bay Program Office. May, 2009. Estimate is based on a study whose results will be presented in a forthcoming publication.

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