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AGRICULTURE'S CONTRIBUTION TO THE REACTIVE NITROGEN LOAD

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Introduction

Reactive N (Nr) refers to all N compounds in the atmosphere and biosphere that are biologically, photochemically, or radiatively active. The Nr pool includes inorganic reduced (e.g. NH_3, NH_4^+) and oxidized (e.g. NO_x, HNO_3, N_2O, NO_3^-) compounds, and organic compounds (e.g. urea, amines, proteins, amides). These Nr compounds are produced by both natural and anthropogenic activities. In the past 100 years, human activities have greatly increased the amount of annual Nr production as a result of increased burning of fossil fuels for energy and industrial fixation of N by the Haber-Bosch process. Anthropogenic Nr sources now exceed natural sources by a wide margin, and the global Nr load is causing detrimental effects on environmental quality. As a result, there is increasing scientific interest in understanding the environmental effects of Nr, identifying the major sources of Nr production and quantifying the amounts produced, and in identifying technologies that can reduce the global Nr load.

Environmental Effects of Reactive Nitrogen

Reactive N is present in all ecosystems because N is an elemental building block of all life forms. In natural ecosystems, plants and animals have evolved elaborate physiological strategies to aggressively scavenge and hoard Nr because it is one of the most limiting elements to growth. As a result, Nr is rarely in excess in natural ecosystems because it is efficiently used and recycled.

In contrast, Nr accumulates in human-dominated systems such as agro-ecosystems and urban-industrial landscapes. Whenever Nr exceeds the immediate needs biological needs of the plants and animals in an ecosystem, it is at risk to cause negative effects on the environment. Excess Nr can threaten environmental quality and human health at both local and global scales as a result of water pollution from nitrate leaching or runoff, air pollution, and greenhouse gas emissions. And because Nr compounds are extremely reactive and mobile, they easily move from one ecosystem to another and cascade through the global environment (Fig. 1). To prevent these negative effects requires knowledge of the major Nr sources and technologies to minimize or eliminate Nr losses to the environment.

Sources of Reactive Nitrogen

The past 110 years has seen a substantial shift in the sources and amounts of Nr creation. In the 1890s, for example, most Nr creation occurred in natural ecosystems as a result of biological N fixation in leguminous plants and other N-fixing plant species and microbial N fixation in soil. Only about 12% of annual Nr creation resulted from human activities, and the total annual Nr emissions to the atmosphere or transfer to water bodies and coastal ecosystems were relatively small (Galloway and Cowling, 2002).

Today, anthropogenic Nr creation is much greater than Nr creation in natural systems as a result of increased food production in agriculture and fossil fuel use in transportation and energy production (Table 1). Fertilizer production by the Haber-Bosch process accounts for 34% of annual global Nr creation, while fossil fuel burning accounts for another 9%. Biological N fixation in natural systems represents only 39% of the global total.

Table 1: Sources and estimated amounts of annual reactive N (Nr) creation terrestrial ecosystems and nitrogen fertilizer production in 1990 (Smil, 1999; Galloway and Cowling, 2002)

Source	**Annual Nr creation (MMT N yr^{-1})**	**Percent of annual global Nr load**
BNF* in natural ecosystems	89	39
BNF* in agro-ecosystems	33	15
Haber-Bosch reduced N	85	37
(N fertilizer for crop production)	(78)	(34)
Fossil fuel combustion	21	9
Total	**228**	**100**

**BNF = biological nitrogen fixation by legumes and other N-fixing plants and microbes.*

Regional patterns of Nr creation largely follow the geographic location of agricultural production, food consumption, and energy use. As such, there is tremendous unevenness in both the total amounts and per capita contribution to Nr creation. Asia accounts for the greatest amount of Nr, per capita use is relatively small because of relatively low caloric intake in diets that are mostly comprised of vegetarian foods and minimal energy use for transportation, heating and cooling (Table 2). North America has the highest per capita Nr creation due to diets rich in livestock products and energy use for automobile transportation, heating and cooling. Hence, most of although the reasons for such large but for different reasons.

Table 2: Annual anthropogenic creation of reactive N and per capita reactive N creation in the mid 1990s (Galloway and Cowling, 2002).

Region	**Reactive N load (MMT N yr^{-1})**	**Per capita reactive N load (kg N per person yr^{-1})**
Asia	69	17
North America	29	100
Europe and FSU	27	44
Latin America	9	19
Africa	5	7
World	**140***	**24**

**Also includes a relatively small contributions from Oceania*

The global Nr load is projected to increase substantially as a result of population growth and economic development. Most of this increase is expected to occur in developing countries because 95% of total population increase will occur in these countries and the rate of economic development will be much greater than in developed countries. Without a major effort to minimize Nr creation associated with economic development and food production, the global Nr load will increase substantially and is likely to cause irreparable damage to environmental quality, human health, and conservation of natural resources and biodiversity (Matson et al., 2002; Wolfe and Patz, 2002).

Minimizing Agriculture's Contribution to the Reactive Nitrogen Load

As a basic building block of protein in all plant tissue, there is a tight correlation between grain yield and the amount of N in crop biomass(Cassman et al., 2002). As food demand increases due to population growth and economic development, crops must take up additional N to produce greater biomass and yield. Substantially higher yields are needed on existing cultivate land because almost all good quality arable land is currently under crop production and it is preferable to avoid expansion of agriculture at the expense of the remaining natural rain forests, wetlands, and grassland savannahs(Tilman et al., 2002; Cassman et al., 2003).

About 80 MMt of N is applied as fertilizer to agricultural systems on an annual basis worldwide (Table 2). Legumes provide another 33 MMt, which means that two-thirds of all N inputs to agricultural systems come from fertilizer. Because there is little scope to increase the N contribution from legume BNF, increased crop yields and crop N demand must be met by N fertilizer. Substantial increases in N fertilizer efficiency will be required to minimize losses of Nr to the environment.

Despite the importance of N fertilizer efficiency in minimizing environmental degradation, there are few studies in which actual on-farm N fertilizer efficiency have been measured across a representative population of farms in major cereal production systems. Measurements under actual on-farm conditions are required because estimates obtained from small research plots tend to overestimate efficiency (Cassman et al., 2002). The few studies in which on-farm measurements have been made indicate that N fertilizer uptake efficiency is relatively low (Table 3). In general, only 30-40% of applied N fertilizer is actually taken up by the crop, which means that the remaining 60-70% is at risk for losses to leaching, runoff, volatilization, and denitrification—all of which can lead to environmental damage. Some of the applied N fertilizer may become incorporated into soil organic matter, but such incorporation would account for 0-30% of the applied N and only occurs in cropping systems where there is net carbon sequestration is occurring. Assuming 35% N fertilizer uptake efficiency and that 15% of the applied N is incorporated into soil organic matter, then 50% of the applied N fertilizer is lost, on average, from agricultural systems worldwide under current cropping practices. Global N losses would amount to nearly 40 MMT of Nr that would cascade through the Earth's ecosystems.

Increasing N fertilizer efficiency is the key to reducing Nr losses from agricultural and the presentation at the IFA conference will focus on exciting new technologies and scientific understanding that will help achieve this goal. Recent publications have also provided comprehensive treatment of this topic(Cassman et al., 2002; Dobermann and Cassman, 2002). But these advances will not be adequate to achieve the needed level of N fertilizer efficiency without adequate investment in agricultural research and extension. Indeed, very little funding is available at national and international levels for research that explicitly attempts to achieve a substantial increase in crop productivity while concomitantly achieving a substantial increase in N fertilizer efficiency and improving soil quality. Without such funding, it will be difficult to meet the demand for food while protecting environmental quality and conserving natural resources, and the challenge of dealing with a rapidly increasing global Nr load is perhaps the single greatest component of this challenge.

Table 3: Best current estimates of average on-farm N fertilizer uptake efficiency for the maize, rice, and wheat in some of the most productive cereal cropping systems of the world. All values based on direct measurements made in farmer's fields.

Crop	**Region**	**N fertilizer (kg ha-1)**	**Efficiency* (% of applied N)**	**Reference**
Maize	USA	103	37	(Cassman et al., 2002)
Rice	Asia	117	31	(Dobermann et al., 2002)
Wheat	India	123-146**	18-49**	(Cassman et al., 2002)

**Proportion of applied N fertilizer taken up by the crop and recovered in crop biomass at physiological maturity.*

***On-farm measurements were made in two consecutive years in a major rice-wheat production domain in India. In 1998, yields and efficiency were very low due to poor weather conditions, while in 1999 yields were higher and efficiency was higher due to favorable weather for wheat production.*

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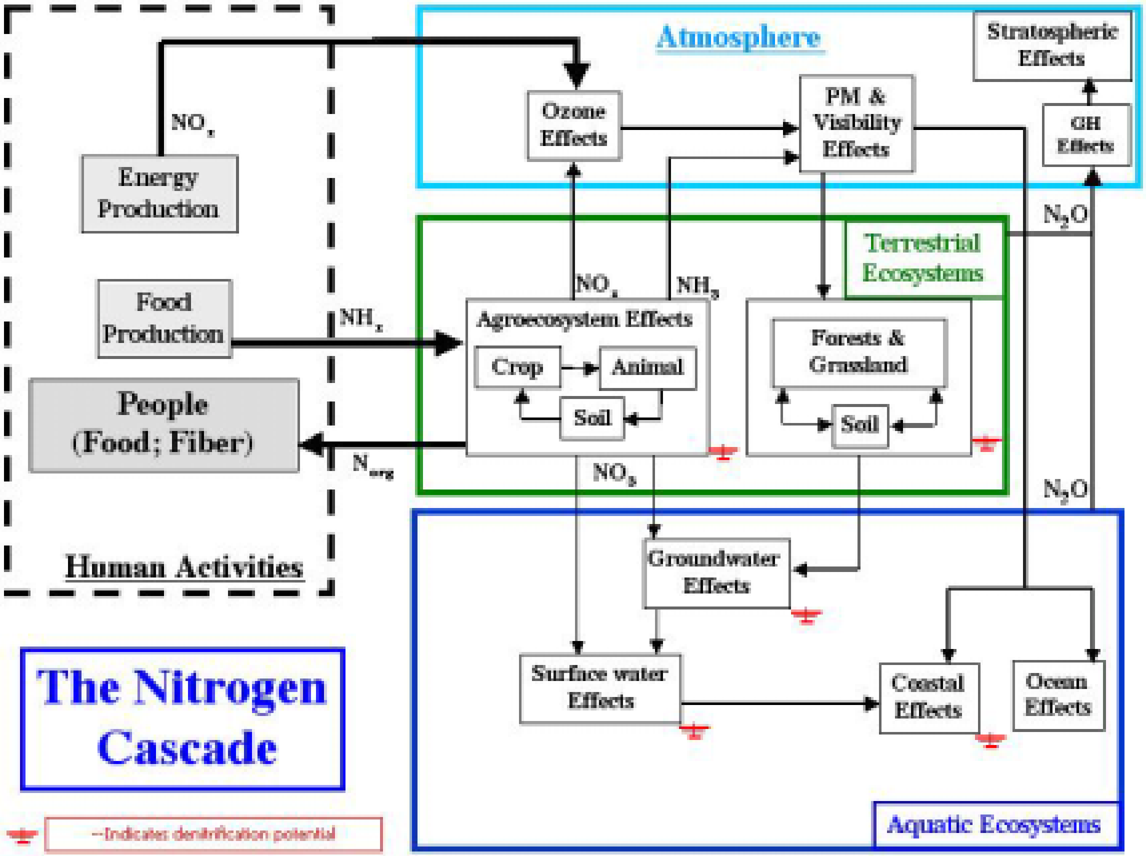

Figure 1: The cascade of effects from reactive nitrogen in the environment (from (Galloway and Cowling, 2002).