Sustainable Management of the Nitrogen Cycle in Agriculture and Mitigation of Reactive Nitrogen Side Effects

International Fertilizer Industry Association

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IFA Task Force on Reactive Nitrogen

International Fertilizer Industry Association
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International Fertilizer Industry Association
28, rue Marbeuf, 75008 Paris, France
Tel: +33 1 53 93 05 00 Fax: +33 1 53 93 05 45/ 47
publications@fertilizer.org www.fertilizer.org

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SYMBOLS, UNITS, ABBREVIATIONS AND ACRONYMS

Symbols

C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
H	Hydrogen
HNO_3	Nitric acid
N	Nitrogen
N_2	Dinitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
NH_x	$NH_3 + NH_4^+$
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_2^-	Nitrite
NO_3^-	Nitrate
NO_x	Nitrogen oxides ($NO + NO_2$)
NO_y	NO_x plus other N oxides such as nitric acid, etc.
O	Oxygen
O_2	Dioxygen
P	Phosphorus
S	Sulphur
SO_2	Sulphur dioxide

Units

bu	Bushel
g	Gram

GJ	Gigajoule
ha	Hectare
kg	Kilogram
l	Litre
lb	Pound
mg	Milligram
Mt	Million metric tonne
t	Metric tonne

Abbreviations and Acronyms

BNF	Biological nitrogen fixation
NBMPs	Nutrient best management practices
DNA	Deoxyribonucleic acid
EEA	European Environment Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross domestic product
GHG	Greenhouse gas
IFA	International Fertilizer Industry Association
INI	International Nitrogen Initiative
IPCC	Intergovernmental Panel on Climate Change
MA	Millennium Ecosystem Assessment
NUE	Nitrogen use efficiency
RNA	Ribonucleic acid
SCOPE	Scientific Committee on Problems of the Environment
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
US or USA	United States of America
UV	Ultraviolet
WHO	World Health Organization
(p)	Projection

1. INTRODUCTION

Nitrogen (N) is a vital element for life. It is an essential component of all proteins and of deoxyribonucleic acid (DNA).

On Earth, there are two pools of N, with relatively little exchange between them: the gaseous dinitrogen (N_2) of the atmosphere, which makes up about 99% of total N, and the 1% of N that is chemically bound to other elements such as carbon (C), hydrogen (H) or oxygen (O) and has been described as “reactive nitrogen” for its tendency to react with other elements (Galloway *et al.*, 2004). Reactive N includes inorganic reduced forms (e.g. ammonia [NH_3] and ammonium [NH_4^+]), inorganic oxidized forms (e.g. nitrogen oxides [NO_x], nitric acid [HNO_3], nitrous oxide [N_2O], nitrate [NO_3^-] and nitrite [NO_2^-]) and organic compounds (e.g. urea, amines, proteins and nucleic acids). Nitrogen in humus (decomposed organic matter found in soil) can be regarded as reactive in the long term only.

Gaseous N_2 cannot be used directly by plants, with the exception of some plant species (e.g. legumes) that have developed symbiotic systems with N_2-fixing bacteria. Owing to the strong bond between its two N atoms, N_2 is almost inert and thus non-reactive. It requires a high energy input to convert N_2 into plant available, reactive N forms.

The N cycle refers to the circulation of N compounds through the Earth's atmosphere, hydrosphere, biosphere and pedosphere. At various points in this cycle, reactive N compounds become involved in processes that can affect human health and the environment in both positive and negative ways.

Additions of reactive N to soils are mainly from fertilizer, manure and biosolids applications, although atmospheric N deposition from combustion sources such as power plants and transportation fuels may also be significant in certain areas.

Appropriate N inputs enhance soil fertility, sustainable agriculture, food security (enough calories) and nutrition security (appropriate supply of all essential nutrients, including protein). On the other hand, when improperly managed, N inputs can be associated with a number of adverse effects on both the environment and human health. Lack of reactive N in the agro-ecosystem leads to soil fertility decline, low yields and crop protein content, depleted soil organic matter, soil erosion and, in extreme cases, desertification. Excess amounts of NO_3^- may move into groundwater and drinking water supplies, raising treatment costs faced by municipalities. Excess NO_3^- in drinking water wells also can be an issue in rural areas that are adjacent to farmland. In surface water, increased loading of N-based nutrients can play a role in eutrophication, a process that contributes to ecological and resource degradation. In the atmosphere, NO_x and particulate matter can exacerbate several human health problems, from asthma to heart disease. Increasing the N_2O concentration in the atmosphere contributes to global warming.

Adopting an integrated approach to nutrient management maximizing the benefits and minimizing the risks associated with the use of N sources contributes to raising crop productivity and N use efficiency.

2. THE NEED FOR FERTILIZER NITROGEN IN AGRICULTURE

2.1. The vital role of nitrogen

Nitrogen is an essential constituent of all life on the Earth and is found in many organic molecules. In particular, it is an essential component of amino acids, the basic elements of all proteins, including enzymes, and of nucleic acids, the building blocks of DNA and ribonucleic acid (RNA). Without N, life and ecosystems would not exist in their current forms.

Nitrogen stimulates root growth and crop development, promotes high protein content, and improves the uptake of the other essential plant nutrients. Crops, with the exception of legumes that fix N_2 from the atmosphere through symbiotic biological N fixation, usually respond quickly to applied N.

Leaf chlorosis (yellowing) starting on older leaves and stunted plants are the main visual symptoms of N deficiency (Picture 1). Most importantly, N deficiency results in severe yield losses and low crop protein content.

Nitrogen is the most important nutrient in terms of fertilizer consumption.

Picture 1. Nitrogen deficiency symptom in oats (Credit: BASF)

2.2. Why are nitrogen fertilizers needed?

Put simply, N moves from the soil to the plant, and back from the plant to the soil, often with animals or humans as intermediates. The real situation is however more complex as N compounds undergo a number of transformations in the soil (mineralization, immobilization, nitrification and denitrification) and are exchanged between soil and the atmosphere (through volatilization, denitrification, biological N fixation, atmospheric deposition) and between soil and the hydrosphere (through leaching, erosion/runoff, irrigation). These transformations and fluxes constitute the soil N cycle (Figure 1).

In natural ecosystems, this cycle is more or less closed, with N inputs balancing N losses. However, the small amount of N moving in the cycle in most natural ecosystems limits biomass production.

In agricultural systems, the cycle is disturbed by the export of substantial amounts of N in harvested products. Consequently, application of fertilizers containing N and other crop nutrients is essential to balance inputs and outputs and so maintain or improve soil fertility, increase agricultural productivity and, in turn, preserve natural ecosystems and wild habitats from conversion to farming.

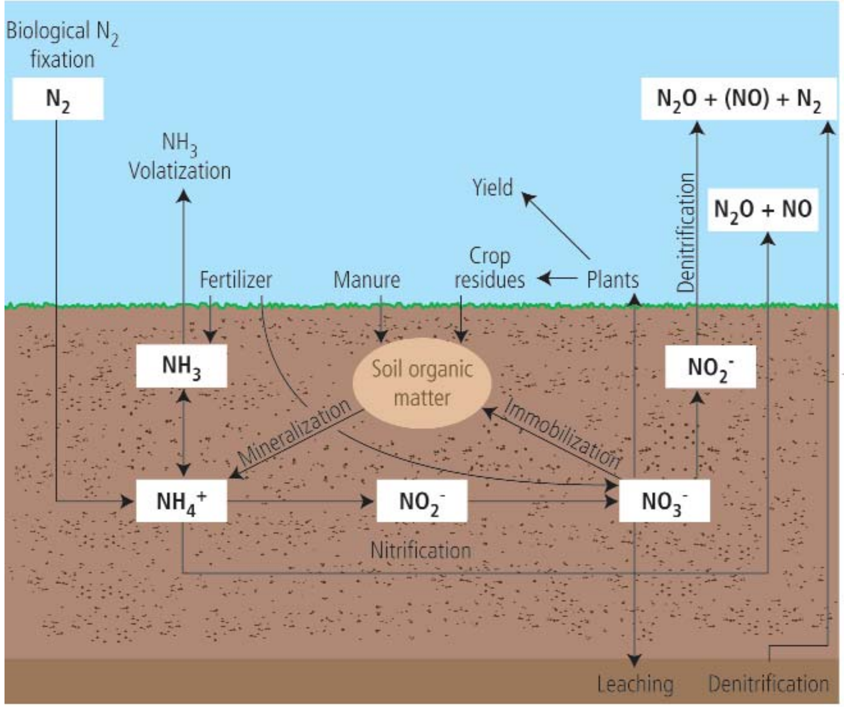


Figure 1. The soil nitrogen cycle (Adapted from Hofman and Van Cleemput, 2004)

2.3. Potential of the different nitrogen sources to meet demand

2.3.1. Atmospheric deposition

Nitrogen compounds that are released to the atmosphere through industrial or agricultural activities return to land or oceans through wet and dry deposition processes. Depending on the N compounds, these processes can involve either local or long-range fluxes. Therefore, the magnitude of N atmospheric deposition depends partly on distance from the emission's source. Geographical distribution of inorganic N deposition in the early 1990s is illustrated in Figure 2.

Atmospheric N deposition is generally between 10 and 50 kg N/ha/year in the main agricultural regions (e.g. Eastern China, Indo-Gangetic Plain, US Corn Belt, West Europe), but can reach up to 80 kg N/ha/year in the North China Plain (Zhang *et al.*, 2006). These amounts are significant for agriculture and must be taken into account when deciding on fertilizer N requirements. However, some atmospheric N input occurs at times of the year when crops are not growing. Therefore, only part of this N may need to be accounted for in a crop N budget.

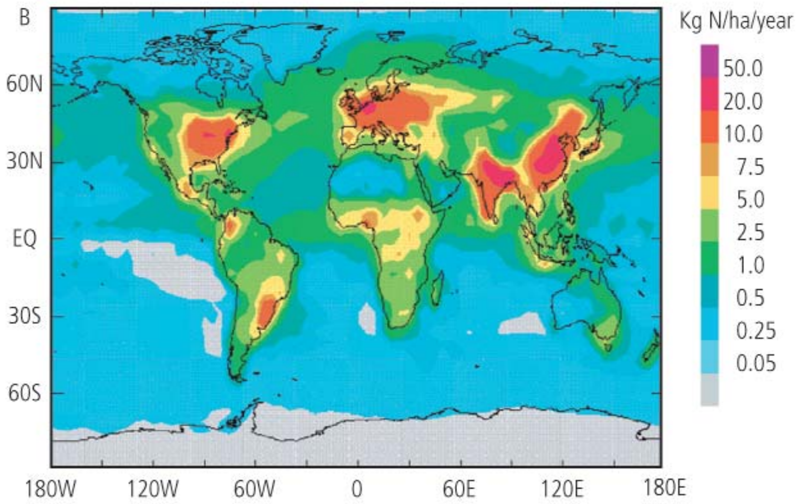


Figure 2. Spatial patterns of total inorganic nitrogen deposition in the early 1990s (Adapted from Galloway *et al.*, 2004)

2.3.2. Organic sources

Organic sources of nutrients mainly comprise soil organic matter, crop residues, green manures, animal manures and urban wastes (biosolids).

Organic materials are valuable sources of plant nutrients, and their application contributes to the improvement of soil physical properties (structure and water retention capacity). However, organic materials can vary widely in N content depending on the fertility of the soil on which a green manure crop or a crop residue is produced, the diet of the animals producing manure, the origin of urban wastes, and the storage and application methods used. Wherever possible, organic materials should be analyzed for their N content before they are applied.

Nutrient release from organic matter in the soil (mineralization) is a function of microbial action. The rate at which N becomes available through mineralization depends, amongst other things, on the nature of the organic matter, climatic conditions and soil type. The seasonal pattern of N release through mineralization is often different from that of crop uptake leading to accumulation of mineral N in the soil at certain times in the year and to losses to the environment.

Successful utilization of N in organic materials requires knowledge of (i) the total N content of the material, (ii) the proportion of the N in organic and in mineral forms and (iii) the rate at which organic N is transformed to mineral forms (mineralization rate) in the local environment. Animal manures and urban wastes must be handled in ways that limit losses of N through volatilization. Some organic materials contain significant amounts of heavy metals that can restrict their use. Low nutrient concentration imposes use near the production site as transportation is very costly.

Box 1. Do plants discriminate between organic and inorganic nutrient sources?

No. All nutrients to be absorbed by plants have to be available in their inorganic (sometimes called "mineral") forms, irrespective of their source. Organic N sources must be mineralized to NH_4^+ and NO_3^- prior to plant uptake.

2.3.3. Biological fixation

Biological N fixation (BNF) is the conversion by living organisms of inert atmospheric N_2 into reactive forms that can be utilized by plants. Symbiotic BNF is accomplished in leguminous plants (e.g. soybean, alfalfa, clover) by host-specific Rhizobium species that, in exchange, obtain energy in the form of carbohydrates from their host plants. Biological N fixation can amount to more than 300 kg N/ha/year in legume-based pastures and is commonly between 50 and 250 kg N/ha/year (Peoples *et al.*, 2004a). Other much less effective symbiotic systems exist in some crops such as sugarcane and rice. Biological N fixation can clearly be a major source of N, especially in systems where legume crops are common in crop rotations. Smil (1999) estimated that BNF from cultivated crops contributes approximately 33 million metric tonnes (Mt) N to agriculture globally. This amount will increase rapidly with the current fast expansion of soybean cultivation.

2.3.4. Manufactured fertilizers

The development of a viable process for the widespread industrial synthesis of NH_3 from atmospheric N_2 (Haber-Bosch process) solved the problem of limited availability of inorganic reactive N for crop production. Manufactured N fertilizers have been a key component of the Green Revolution and they have allowed agricultural production to keep pace with world population growth. It is estimated that fertilizer supplies about half of the total N required for global food production (Mosier *et al.*, 2004). The N input from manufactured fertilizers in 2005/06 was estimated at 90.9 Mt N (Heffer and Prud'homme, 2006).

In comparison to the other N sources, manufactured fertilizers enable the farmer to apply the right product (right N form and right nutrient ratio) at the right rate, right time and right place.

2.4. Efficiency of the different nitrogen sources

Organic materials, BNF and atmospheric deposition ("indigenous N sources") must be taken into account as sources of reactive N in the soil. If due account is not taken, fertilizer N requirements may be over-estimated leading to increased losses of N to the wider environment. However, it must also be recognised that the availability of N from these sources may not be synchronized with crop requirements, and a large proportion of this N may be lost from the soil. Quantifying the N made available from these sources is never easy but the best estimates should be made.

"Effective" N inputs from indigenous sources are insufficient by far to support current levels of global agricultural output. Therefore, they must be supplemented by applications of manufactured N fertilizers.

Unlike indigenous sources, manufactured fertilizers can be applied precisely in terms of timing and amount. Their N content is known and their uniform composition is allowing accurate application. Fertilizer applications can be split to meet the varying requirements of a crop as growth progresses. The ratio between nutrients (N, P, K, S, Mg, Ca and micronutrients) can be adjusted to site-specific needs; balanced nutrition helps to improve N use efficiency (NUE, see Box 2, page 29 for definitions). As a consequence, the use efficiency of N from manufactured fertilizers can be much higher than that of N from indigenous sources. Nevertheless, in practice, this overall efficiency remains low, around 40% in the year of application on average at the global level, i.e.

well below efficiency levels (up to 90% in the year of application) observed in well-managed research plots (Balasubramanian *et al.*, 2004).

Low N use efficiency is due to a number of inevitable losses through (i) nitrification/denitrification, (ii) NH_3 volatilization, (iii) NO_3^- leaching and (iv) runoff/erosion of particulate matter. Nitrogen is lost from the field through these pathways (Figure 3). Immobilization of N in soil organic matter also competes with plant uptake and lowers the plant-availability of N. However, immobilized N is not lost from the field, but remains in the soil where mineralization will slowly make it available again to plants. As a result, average NUE at the global level over a multi-year period is higher than the 40% observed during the year of application, as part of the N applied is taken up by the crops in subsequent years.

Nitrogen use efficiency can be improved by limiting overall N losses. However, when limiting losses through one pathway, there is a risk of increasing losses through another. Therefore, all the pathways for N loss must be considered simultaneously to ensure that there is an overall agronomic and environmental benefit from adopting new farming practices. Similarly, from a policy/regulatory point of view, it makes little sense to address N losses to the atmosphere independently from those to the hydrosphere. Because of the diversity of crops, soil and climate conditions and N sources, and of the complexity of the N cycle, it is important to use a holistic approach and to develop strategies tailored to local requirements.

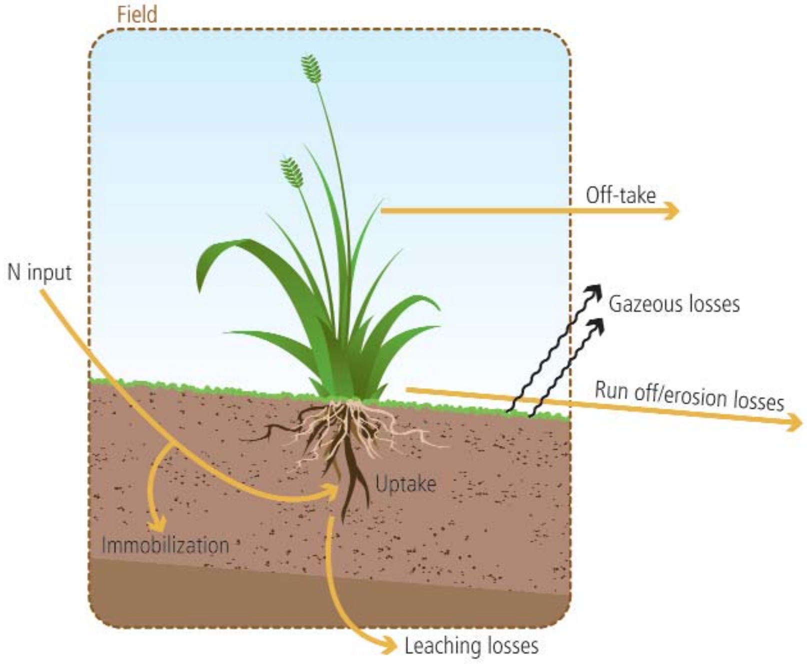


Figure 3. Schematic diagram indicating the interactions between N input and N loss processes (Adapted from Peoples *et al.*, 2004b)

3. AGRICULTURE AND THE GLOBAL NITROGEN CYCLE

3.1. The nitrogen cycle: sources and sinks of nitrogen in the environment

3.1.1. The global nitrogen cycle

Figure 4 shows the global N cycle during the early 1990s. The orange dotted line surrounds the total pool of reactive N. The arrows going in and out of the box indicate the exchange between non-reactive N_2 and the pool of reactive N. The total amount of reactive N fixed from atmospheric N_2 was estimated at 268 Mt N per year in the early 1990s.

A portion of the N fluxes is due to human activities, and part to nature. For instance, N_2 is fixed through BNF in both natural systems (N-BNF) and agricultural or cultivated systems (C-BNF), with natural systems being the main contributor. Among the inputs of anthropogenic origin, the Haber-Bosch process is the main source, but some of the reactive N produced through this process is for non-fertilizer uses (e.g. for industrial or feed uses).

Reactive N is subject to many conversion and translocation processes in the environment (crop uptake, leaching, gaseous losses, etc). Figure 4 shows the gaseous emissions of NO_x and NH_3, which are then deposited partly on land, partly at sea. There is also an N cycle within each continent, not shown in the figure, for example with leaching from land to groundwater and to surface water.

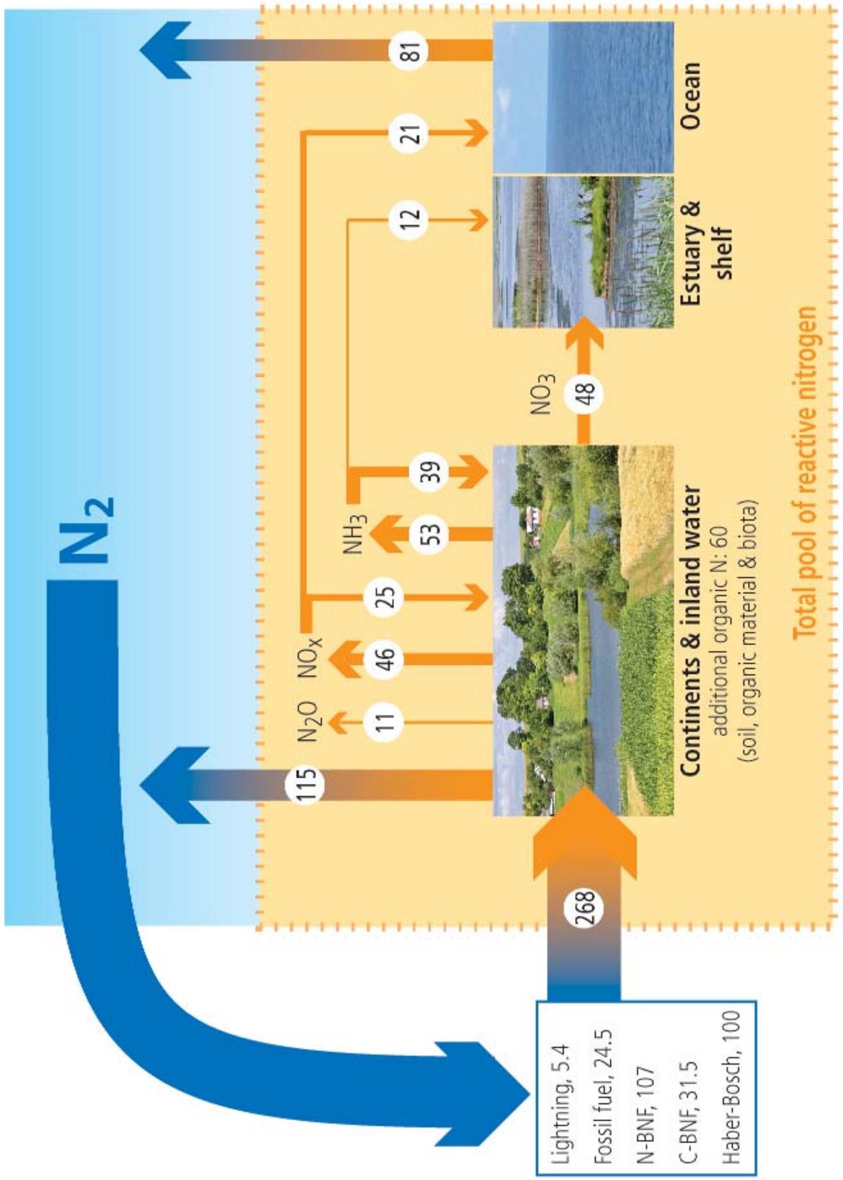


Figure 4. Components of the global N cycle for the early 1990s (Million t N/year) (Adapted from Galloway *et al.*, 2004)

The final fate of the reactive N annually entering the global N cycle is either denitrification back into the atmospheric pool of non-reactive N_2 (~73% according to Galloway *et al.*, 2004) or accumulation into the organic N pool (~22%) in the form of organic soil N, organic material (e.g. manure, crop residues, human waste) or living organisms. A small, but environmentally relevant, fraction is converted into N_2O, a compound contributing to global warming, which is considered to be reactive N despite its half-life time of more than 100 years.

Great uncertainties still exist regarding the input and output values, but it is evident that N fluxes have increased through human activity. Developments in regional fertilizer consumption (IFA, 2006) indicate that significant changes continue in some areas.

3.1.2. The role of agriculture

Ideally, losses of reactive N from agricultural areas should be no greater than those from natural ecosystems. It is often thought that agriculture should have its own, closed N cycle, that all the nutrients would remain in the "agricultural box", and that it should be possible to produce the same amount of food year by year without external N inputs (Figure 5). This "closed cycle" model

Figure 5. The perceived "ideal" agricultural N cycle: a closed system without losses

includes humans as an integrated part of the cycle. To succeed, virtually all of the planet's six billion consumers would need to reside on or very near a farm in a kind of peasant agriculture or village lifestyle.

The actual situation is quite different from this perceived “ideal” scenario. There are essentially two reasons why agricultural production is not, and cannot be, sustainable without external N inputs, for example in the form of manufactured fertilizer.

- First, the agricultural N cycle is disrupted and leaks at several points (Figure 6). Some of the N emissions to the air and water are inevitable losses. The main leaks in the agricultural N cycle are volatilization of NH_3, leaching of NO_3^- and N_2 losses after denitrification of NO_3^-. Smaller amounts of NO_x and N_2O are also lost from the agricultural system.

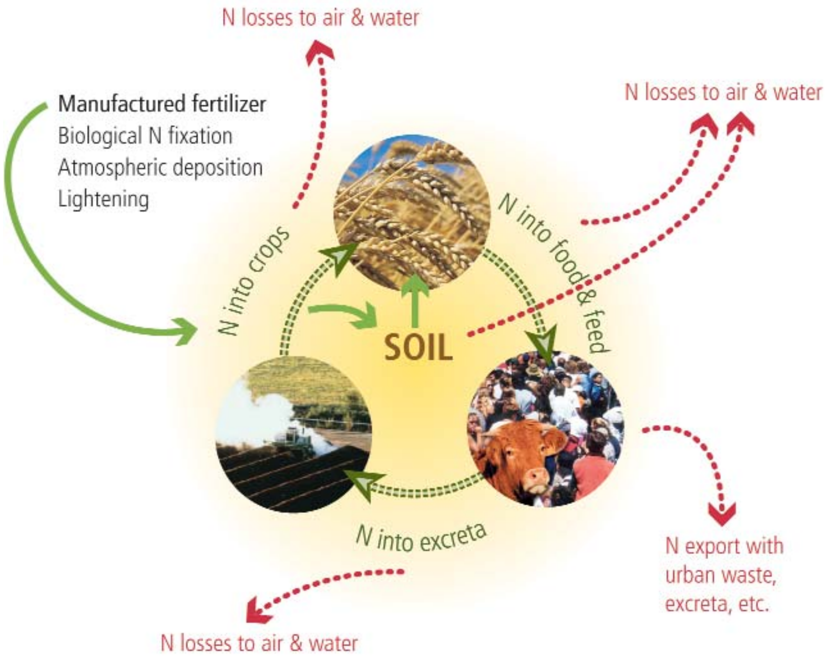


Figure 6. The actual agricultural N cycle: an open system with inevitable losses

On average at the global level, agricultural production is responsible for about 75% of total NH_3 emissions. Within agriculture, animal wastes account for more than 50% of NH_3 emissions, manufactured fertilizer for 22%, direct emissions from crops for 9% and human wastes for another 7%. The remaining approximate 10% is from the burning of agricultural wastes, forests and savannas (Galloway *et al.*, 2004).

Nitrogen is also lost from agricultural soils through leaching of NO_3^-. Nitrate is water-soluble and, therefore, mobile in the soil. If not taken up by the crop and if there is a water surplus in the soil, NO_3^- moves into ground and surface waters. Once NO_3^- has left the crop's rooting zone, it is usually lost for crop production.

In the field, typically about 10% of applied N is lost as N_2 and, to a much lower extent, as N_2O through denitrification. There is great variability in denitrification rates depending on soil, crop and climatic conditions. The major denitrification sites in the global N cycle are not actually agricultural soils: wetlands, freshwater systems and, in particular, estuaries, coasts and the open sea.

- Second, agricultural production is constantly increasing in response to the fast growing world population and to changing eating habits (Bruinsma, 2003). Consumption of animal proteins tends to increase with per capita income. More meat requires more feed. The current, very rapid development of bioenergy demand calls for a further increase in agricultural output. In a “closed” N recycling system (Figure 5), it would be impossible to increase food, feed, fibre and bioenergy production to meet current demand in a sustainable manner because the amount of available N would limit output.

3.2. Pathways of nitrogen in the environment

Reactive N released into the wider environment from agriculture, or to the air from fossil fuel combustion, can contribute to harmful environmental and human health effects. Once in a reactive form, N can participate in a sequence of chemical reactions leading to forms that have different effects in the atmosphere, in terrestrial and aquatic ecosystems and on human health. Galloway *et al.* (2003) described this sequence of effects as “the nitrogen cascade”, although the word cascade implies more a one-way process than a complex cycling (Figure 7). For example, N_2 that has been converted to NH_3

during the Haber-Bosch process can be used to produce urea. After application of urea to a field, part of the fertilizer is lost as NH_3 to the atmosphere. There, the NH_3 may contribute to dust formation, which can have negative consequences for human health. After deposition on a forest soil, the NH_3 may enhance soil acidification. In the soil, the NH_3 is nitrified to NO_3^-, which, if not taken up by plants, may be leached to groundwater and, thereafter, enter the surface water system, where it may contribute to eutrophication problems. Finally, the NO_3^- may be denitrified back to N_2. This is a theoretical example, which illustrates how reactive N may take various pathways through the environment, with sequential effects before it is converted back to non-reactive N_2.

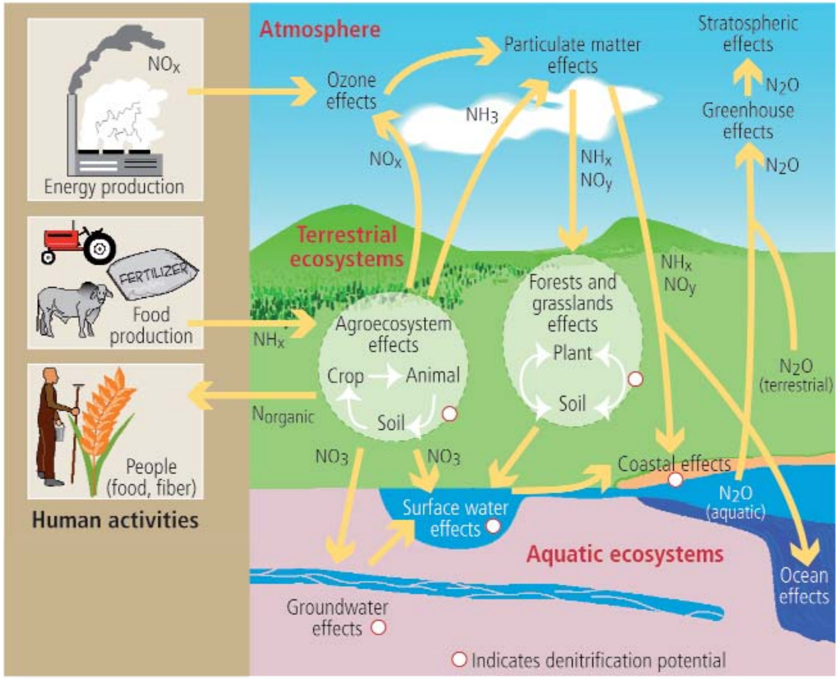


Figure 7. The "Nitrogen Cascade": sequential effects of reactive nitrogen forms in the environment (Adapted from Galloway *et al.*, 2003)

3.3. Environmental and human health effects: what we know, what we guess and what we do not know

Sustainable agricultural production relies on the external input of “fresh” mineral N, as manufactured N fertilizer or biological N fixation, in order to fill the gap caused by N losses and increasing food demand. The continuous challenge for the farmer is to apply the right N product at the right rate, right time and right place in order to sustain optimum yields and, at the same time, to avoid excess application. Both lack and excess of N may result in adverse effects on human health, the environment and farmer's income.

3.3.1. Effects of lack of nitrogen

The effects of not applying appropriate amounts of N fertilizer in crop production are particularly obvious in the long term. Continuous cropping without replacement of the removed plant nutrients results in reduced soil fertility, erosion and declining yields. The effect of “mining the soil for nutrients” is illustrated in Picture 2. Resulting food insecurity (insufficient availability of food) and nutrition insecurity (low protein content and food quality) have numerous social and human health effects. If the farmed land no longer provides enough nutritious food, farmers are forced to cultivate new

Picture 2. Field trial with maize in western Kenya (Credit: Paul Seward, FIPS)

additional land, which is scarce in most regions and may include fragile, biodiversity-rich ecosystems that should be protected. In extreme cases, not replacing soil nutrients that are lost through various pathways can result in irreversible desertification.

Nitrogen plays an important role within plant nutrition because it is involved in many biological processes and it is required in large quantities. Consequently, a lack of N can severely reduce yields. In addition, a deficiency in N can result in reduced uptake and inefficient use of the other plant nutrients (phosphorus, potassium, sulphur, etc.). If not taken up by the crop, some of these nutrients may be lost from the soil by leaching or erosion.

3.3.2. Effects of excess nitrogen

Acidification

Acid deposition results mainly from anthropogenic emissions of sulphur dioxide (SO_2), NO_x and NH_3. It damages acid-sensitive ecosystems on a regional to continental scale. In particular, forests and freshwater lakes are sensitive to acidification. Consequences range from defoliation and reduced tree vitality to declining fish stocks and decreasing biodiversity in lakes. Ammonia plays a significant role in the acidification of terrestrial and aquatic ecosystems. Ammonia is responsible for 33% of the acidification effect in Europe, SO_2 and NO_x for 33% and 34%, respectively (EEA, 2002). Gaseous NH_3 emissions return to the surface through dry or wet deposition, partly combined with SO_2 as ammonium sulphate. While most of the dry deposition of NH_3 takes place near the emission site, once combined with nitric or sulphuric acid in the atmosphere, the N can be transported over distances of several thousand kilometres (EEA, 1998).

Eutrophication

Eutrophication is the accumulation of nutrients in aquatic and terrestrial ecosystems that can lead to an undesired increase in biomass production and a shift in species composition. In surface waters, eutrophication is particularly serious where it leads to algal blooms (Picture 3) and subsequent oxygen-consuming decomposition processes, which may result in the death of fish and other organisms. Ammonia emissions that deposit on water bodies and NO_3^- leached from agricultural soils into surface water are some of the main anthropogenic N sources contributing to the eutrophication of aquatic ecosystems. Other major sources of nutrients to water are urban and industry wastes, in particular where wastewater is not, or is insufficiently, treated. These point sources also emit phosphorus (P), which is critical in the eutrophication of freshwater systems since they are generally P-limited. Eutrophication effects occur on the local level in small freshwater systems. But problems also can appear on a regional or even continental scale if long-range transboundary emissions of NH_3 and NO_x deposit on distant water bodies, or if some leached N finally reaches rivers and coasts. In terrestrial ecosystems, eutrophication due to N deposition affects mainly species diversity and composition.

Picture 3. Cyanobacterial bloom in Dianchi Lake, Kunming, China (Credit: Yin Kedong)

Global warming

Short-wave solar radiation heats the surface of the Earth, and the energy is radiated back through the atmosphere at longer wavelengths. Certain gases, for example CO_2 and N_2O, can absorb this longer wavelength radiation, trapping heat in the atmosphere. This “greenhouse effect” is essential for maintaining life on Earth. However, concentrations of these greenhouse gases have increased, apparently due to human activity, leading to a warming of the Earth's average surface temperature (“global warming”). This, in turn, will cause global and regional climatic changes with potentially severe consequences. The main anthropogenic contributors to the enhanced greenhouse effect are: CO_2 (60%), methane (CH_4, 20%), halogenated gases (e.g. CFCs, 14%) and N_2O (6%) (IPCC, 2001). It is estimated that the global warming potential of 1 kg N_2O is equivalent to that of approximately 310 kg CO_2. All ecosystems emit N_2O and more than 50% of the global emission of N_2O is considered "natural" (soils under natural vegetation, oceans, etc.). Agriculture accounts for 86% of the global anthropogenic N_2O emissions (US-EPA, 2006). Of the agricultural N_2O emissions, 44% is related to the management and application of animal manure, and 14% is associated directly with the use of manufactured fertilizer (Mosier and Kroeze, 1998). At the same time, agriculture can mitigate global warming through carbon (C) sequestration (immobilization of C into organic compounds), and N_2O emissions from cropped land can be minimized by adoption of nutrient best management practices (NBMPs).

Stratospheric ozone depletion

Unlike ground-level ozone (a component of urban smog), stratospheric ozone is essential to the health of all living beings. The densest concentration of stratospheric ozone, the ozone layer, exists at an altitude of 15 to 35 kilometres, and it shields the Earth's surface from high levels of ultraviolet (UV) radiation. There is evidence that high exposure to UV B radiation increases the incidence of skin cancer, eye cataracts and sunburn. Historically, ozone-depleting substances (chlorine, bromine) have been emitted as a result of their use, for example as refrigerants or cleaning and degreasing solvents. It has recently been recognized that N_2O, when converted to nitric oxide (NO) in the stratosphere, may act as a catalyst in ozone destruction reactions. However, the overall influence of N_2O on the ozone layer is complex and very different from that of known ozone-depleting substances. A great deal of uncertainty exists regarding the chemical reactions involved. At present, there is no consensus on a quantitative value for the ozone-depleting potential of N_2O.

Particulate matter formation (dust) and photo-oxidant formation ("summer smog")

There is increasing concern about the respiratory and related health problems resulting from particulate matter (PM) that contributes to atmospheric dust formation on a local to regional scale. The main sources for PM10 (particle size <10 µm) are stationary combustion plants, industry and vehicles (EEA, 1998). However, NH_3 from agricultural sources may contribute to PM10 formation as a secondary source after transformation in the atmosphere into ammonium sulphate or ammonium nitrate. In the EU25 countries, the contribution of NH_3 to total PM10 formation was about 13% in 2003 (EEA, 2005). Photo-oxidant formation of reactive chemical compounds such as ozone occurs by the action of sunlight on certain air pollutants. Photo-oxidants may be formed in the troposphere under the influence of UV light, through photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x). Ozone is considered the most important of these reactive compounds, which may be injurious to human health and ecosystems and may also damage crops. International regulations to control ground-level ozone formation (e.g. from UNECE, EU) are in place to reduce these detrimental effects.

Nitrate in drinking water and food

The general public perception is that dietary NO_3^- intake poses a health risk and, therefore, concentrations of NO_3^- in agricultural products and drinking water should be minimized. Despite the fact that the main source of NO_3^- intake is food, not water, the World Health Organization (WHO, 1970, modified in 1993) set a recommended limit for drinking water of 50 mg NO_3^- per litre. The main issue was the microbial conversion of NO_3^- to nitrite (NO_2^-), which was associated with problems involving nitrosamines and methaemoglobin. There is now widespread agreement that human health concerns over NO_3^-, which led to the introduction of the WHO recommendations in 1970, were largely unfounded (L'hirondel and L'hirondel, 2002). The so-called "blue baby syndrome" (methaemoglobinaemia), for example, arises from bacteria-contamination and not from ingesting too much NO_3^- as originally supposed. Similarly, the association of gastric cancer with dietary NO_3^-, which was never supported by epidemiological evidence, has been shown to be only theoretical. Recent work even suggests that ingested NO_3^- provides gastro-intestinal protection against food-borne pathogens and "epidemiological studies show a reduced rate of gastric and intestinal cancer in groups with a high vegetable based nitrate intake" (Leifert and Golden, 2000).

4. FEEDING AN INCREASING WORLD POPULATION IN A SUSTAINABLE MANNER

The vital role of N in all aspects of agricultural production creates an unbreakable linkage between N use and the demands of society for agricultural products and services. Those demands continue to grow in both magnitude and diversity. Throughout the world, they include food, feed and fibre and, in some regions, bioenergy and C sequestration. Additionally, there is a common expectation that productivity from farmed lands will be sufficient to avoid use of marginal lands or conversion of forests and recreational areas to farming.

4.1. Prospects for global demand for agricultural products

Population is a major factor determining agricultural demand. Table 1 summarizes population projections (U.S. Census Bureau) and some other indicators of world food and feed demand developed by FAO (2002, 2004). World population is expected to increase to 8.2 billion by 2030, a 33% increase from the 2000-02 population of 6.2 billion.

Table 1. Indicators of world demand for food and feed (Adapted from FAO, 2002, 2004; U.S. Census Bureau, 2005)

	1979-81	1997-99	2000-02	2015 (p)	2030 (p)
Population (millions)	4453	5930	6156	7203	8206
Consumption (kcal/capita/day)	2552	2803	---	2940	3050
Cereals for food (Mt)	706	1003	---	1227	1406
Cereals for feed (Mt)	575	657	---	911	1148
Meat production (Mt)	132	218	---	300	376
Vegetable oil and oilseed production (Mt oil equivalent)	50	104	---	157	217
Undernourished people in developing countries (millions)	---	777	815	610	443

A 9% increase in caloric consumption per capita is expected from 1997-99 to 2030. Together with a 72% increase in meat consumption and a doubling of oilseed consumption, this reflects substantial dietary changes. These changes will be most pronounced in developing countries (Figure 8). A critical assumption in these projections is a 4% annual increase in per capita gross domestic product (GDP) from the 1997-99 period through 2030 for developing countries.

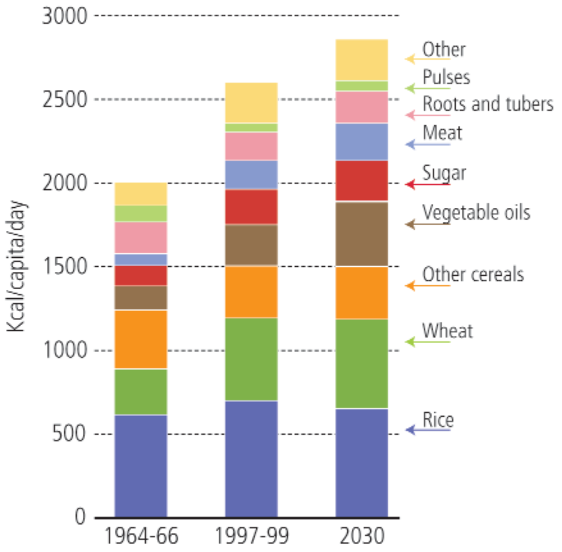


Figure 8. Dietary changes in developing countries (Adapted from FAO, 2002)

These data show that, though food security is expected to continue improve as a result of increased production and poverty alleviation, over 400 million people would still be undernourished in 2030. That number might be much higher if the necessary national and international policies to promote agriculture are not put in place.

Increasing societal demands on agriculture go beyond food and feed. World cotton use is projected to continue increasing at a rate of 1.3% per year (USDA-ERS, 2004). Several recent studies have indicated great potential for land not needed for food, feed or fibre to be utilized for bioenergy production (Aitkin, 2003; Smeets *et al.*, 2004; Perlack *et al.*, 2005). Considering the demand outlook for food and feed in developing countries and anticipated increasing demand for fibre and bioenergy in many parts of the world, it is highly likely that incentives to increase crop production will remain high.

The global crop area is expected to grow only slowly through 2020. It is anticipated that the majority of increases in production will come from higher crop yields (Rosegrant *et al.*, 2001). This will require more intensive and efficient use of agricultural inputs, including nutrient sources, in order to meet world requirements in a way that is economically viable, socially acceptable and environmentally sound.

4.2. Outlook for world nitrogen fertilizer demand

Increased requirements for food and other agricultural products will undoubtedly increase demand for N fertilizers. However, determining the magnitude of the increase is not straightforward. For example, Wood *et al.* (2004) pointed out that the 2.4% average annual growth in food consumption between 1961 and 2001 was accompanied by a 4.5% increase in fertilizer N use. They went on to explain that the increase in fertilizer use was largely due to a change in the structure of food demand, where consumption of meat products grew faster than cereals, increasing the demand for feed grains and for N.

Projections of future fertilizer demand also involve assumptions about N use efficiency (NUE; see Box 2 page 29 for definitions), measured as the amount of production resulting from each unit of fertilizer N used. Will NUE decrease because higher application rates are used and the law of diminishing returns sets in as farmers move up an unchanging N response curve? Or, will it increase due to higher energy and input costs, improved management, better technology and increased awareness of problems associated with inefficient use? Or, will it be business as usual with no change from the past?

After exceptionally strong growth of world fertilizer demand in 2003/04 and 2004/05, Heffer and Prud'homme (2006) forecast that global N consumption would increase from 90.9 Mt N in 2005/06 to 99.4 Mt in 2010/11, corresponding to an average annual growth rate of 1.8%.

Figure 9 illustrates the outcome of longer-term projections of global fertilizer N consumption carried out in recent years by several authors (Bumb and Baanante, 1996; FAO, 2000; Wood *et al.*, 2004; Galloway *et al.*, 2004). All projections point to an increase in fertilizer consumption in the decades to come, but the magnitude of this increase depends greatly on the underlying assumptions. For instance, Wood *et al.* (2004) identified three different scenarios: (i) a scenario following trends since 1969 for both crop production and fertilizer use; (ii) a scenario following the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to project food production, and assuming constant NUE based on 1997 values; and (iii) a scenario based on the IMPACT model for food production projections, and assuming relative NUE gains of 17% from 1997 levels by 2020, and of 30% by 2050. Scenario 1 by Wood *et al.* is seen as unrealistic because, over the next decades, there will be significant changes in crop production and in nutrient management practices, which are not accounted for in the scenario.

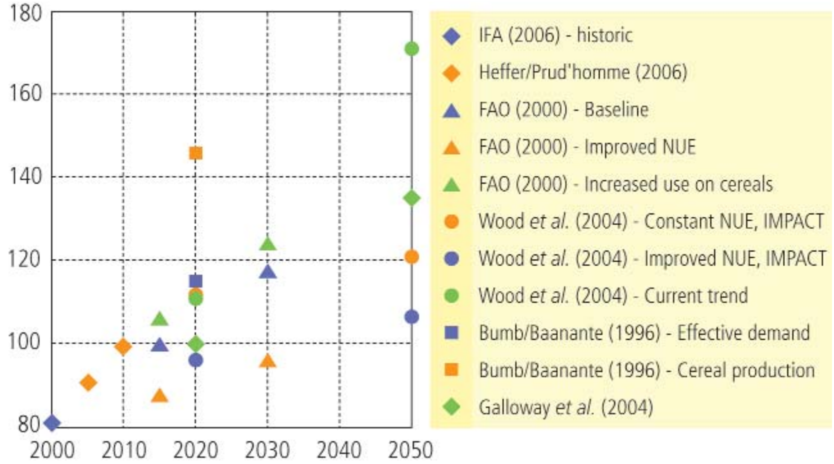


Figure 9. Long-term fertilizer N use projections (Mt N) (Adapted from Millennium Ecosystem Assessment, 2005)

Wood *et al.* (2004) anticipated that fertilizer N use would grow around 1.8% annually in the short term. Average annual growth would then drop to 1.6% by 2020 and to 1.4% by 2050, unless NUE increases. With the NUE gains assumed in scenario 3, average annual growth of fertilizer N use would drop to less than 0.5% after 2010. Another recent analysis looking at crop-specific food production gave similar results but pointed out that such gains in NUE would require substantial additional investment in research and education (Dobermann and Cassman, 2004b). Forecasts to 2010/11 by Heffer and Prud'homme (2006) tended to show that projections by Wood *et al.* under scenario 3 cannot be achieved, as these projections for 2020 would already be exceeded in 2010. Long-term projections are subject to great uncertainty and involve many critical assumptions about our ability to improve crop productivity as demand increases, while also improving NUE. Recent projections indicate that global demand for N fertilizers in 2050 could be between 107 and 171 Mt N. According to the four scenarios of the Millennium Ecosystem Assessment (2005), global fertilizer N consumption in 2050 is anticipated to be between 110 and 140 Mt N.

4.3. Improving nitrogen use efficiency

The extent to which increased demand for agricultural productivity will affect future N use is greatly influenced by the NUE of the production systems. Similarly, the quantity of N lost from tomorrow's agro-ecosystems to water or to the air will be set by the NUE of the systems adopted. So, a critical issue is the potential for improving NUE in both the year of application and over longer periods relative to current levels.

It has been estimated in studies of farm fields, that 20 to 50% of the N applied in fertilizer is recovered in the crop during the year of application in today's major cereal cropping systems (Cassman *et al.*, 2002). By contrast, recovery of 60 to 80% is common in small well-managed research trials and has approached 90% under irrigation (Balasubramanian *et al.*, 2004; Doberman and Cassman, 2004a; Krupnik *et al.*, 2004; Fixen *et al.*, 2005). This difference between farm measurements and research plots indicates that there is a good opportunity for increasing on-farm NUE by improving farm-scale technologies and practices such as those discussed in section 5 of this paper. However, the inevitable N losses in a biological system, where many uncontrollable factors influence the N cycle and crop growth, set an upper limit on N efficiency as the small, carefully managed research plot results demonstrate.

Good improvement in on-farm NUE is occurring in some major cropping systems. For instance, maize receives the largest amount of N fertilizer in North America. Since 1965, maize grain yields have increased regularly, while fertilizer N use per area unit has remained almost stable since around 1980 following a period of rapid increase (Figure 10).

As a result of these two factors, NUE for grain maize production in the USA declined rapidly in the 1960s, but has been steadily improving since the mid-1970s (Figure 11). This is a major achievement as increasing NUE without enhancing crop productivity would make little sense in the current context of fast growing world demand for agricultural products. Contributing factors to this increase were probably (i) more vigorous crop growth associated with increased yields and genetic improvement in stress tolerance, (ii) general improvement in cultural practices and (iii) better matching of the rate and timing of applied N to crop demand and to N supply from indigenous sources (Dobermann and Cassman, 2004).

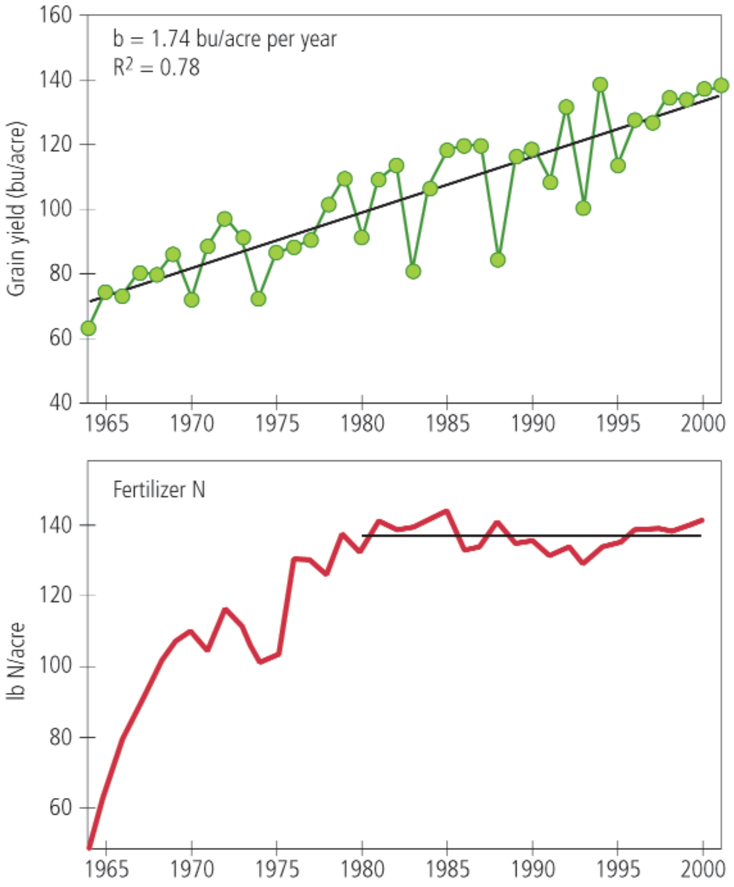


Figure 10. Evolution of grain yield and fertilizer N use in maize in the USA (Adapted from Cassman *et al.*, 2002)

Similar gains in NUE have been occurring for cereals in Western Europe. For instance, in France, grain production has increased about 50% since 1980, while fertilizer N use has increased less than 10% over the same period (UNIFA, 2005).

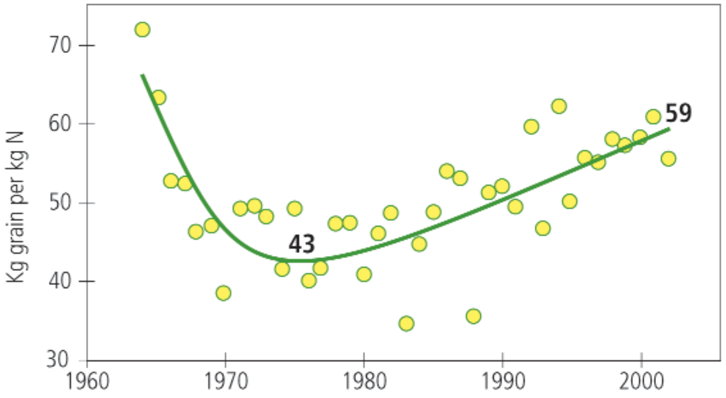


Figure 11. Fertilizer N use efficiency trends for US maize (Adapted from Fixen and West, 2002)

In many parts of the world, in particular in most developing countries, NUE measured as the amount of food produced by unit of N applied ("partial factor productivity"; see Box 2 page 29 for definitions) continues to decline, as exemplified by trends over the past two decades in China and India, the two largest N fertilizer markets (Figure 12). It is worth noting that NUE in India seems to have stabilized since 1997. The steady decline of NUE in China and the low NUE levels compared to India (23 kg cereals/kg N in China vs. 28 kg in India) can be explained partly by the very rapid growth of fruit and vegetable production in China, leading to an over-estimation of N fertilizer being applied to cereals in that country.

At the global level, NUE for cereal production dropped sharply until the beginning of the 1980s, and then remained stable over two decades (Figure 13). Assuming two-thirds of world fertilizer N is applied to cereals, current NUE (expressed as partial factor productivity) is around 33 kg cereals/kg N.

With an expected change in NUE trends in some of the main fertilizer-consuming developing countries, an increase of average NUE at the global level

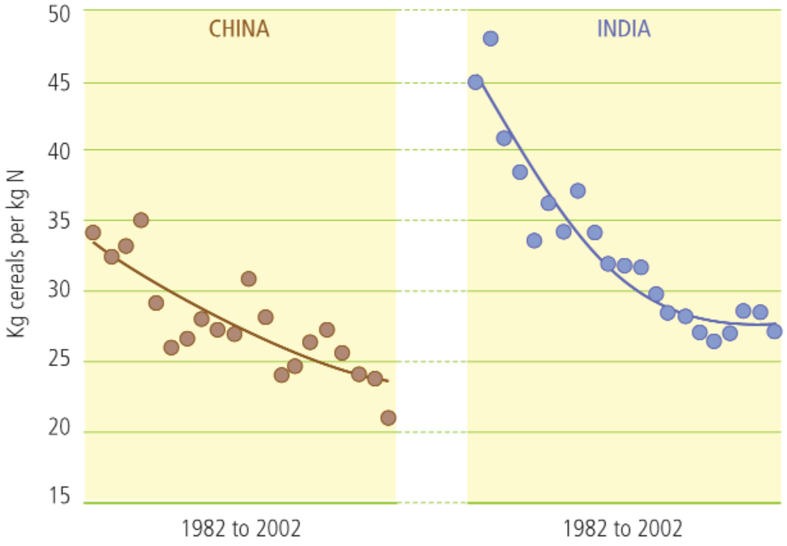


Figure 12. Fertilizer N use efficiency trends for cereal production in China and India[1]

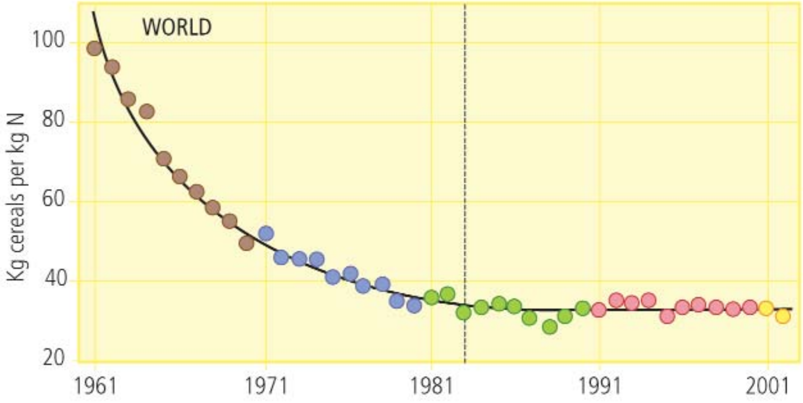


Figure 13. Fertilizer N use efficiency trend for global cereal production[1]

[1] These figures have been generated using FAOSTAT (FAO, 2006) for cereal production and IFADATA (IFA, 2006) for N fertilizer consumption, under the assumption that two thirds of fertilizer N is applied to cereals.

might be observed by the end of the decade. However, to achieve this, much remains to be done.

Several technologies and practices hold promise for improving NUE while maintaining the potential for increasing agricultural production. Unfulfilled potential for each of these technologies or practices varies markedly around the world, depending on current practices and local constraints to technology adoption. Some possible opportunities, including several highlighted by Giller *et al.* (2004), are:

- Increasing yield potential and yield stability through genetic improvement and crop management;
- Balanced nutrition to allow optimum utilization of available N;
- Split N applications to better match N requirements of crops through the growing season;
- More efficient fertilizer products that better synchronize N release and crop N demand (e.g. slow- and controlled-release fertilizers);
- Fertilizer additives to reduce N losses (e.g. urease and nitrification inhibitors);
- Site-specific N management – prescriptive (before planting), corrective (using in-season diagnostic tools), or both;
- Decision support systems: computer-based models or simple field assessment tools and interpretation aids;
- Genetic improvement in N recovery or N utilization efficiency of some crops (primarily those having received little attention by breeders in the past).

Some of the items listed above will require investments in additional research before they make a significant impact, while others primarily require expanded education and technology transfer efforts. In the medium term, more significant gains in NUE can be expected from the adoption of NBMPs (using the right product at the right rate, right time and right place) customized to local conditions rather than from the enhancement of NUE at the genetic level. A good example is the incorporation of balanced nutrition in nutrient management programmes, where the objective is to ensure that crops receive adequate amounts of all nutrients from either indigenous sources or supplemental applications. A recent review of the impact of balanced nutrition on NUE showed that the average fertilizer N recovery efficiency across studies in China, India and North America was 54% for balanced treatments, but dropped to 21% for conventional or check treatments (Fixen *et al.*, 2005).

Farming regions with high concentrations of livestock present a major challenge to agriculture with regard to global reactive N. The global recovery by crop plants of N from animal wastes has been estimated at about 15% (Oenema and Tamminga, 2004). The authors indicated that, on a global scale, only about 25% of the N voided by livestock is recycled to cropland. The lowest NUEs typically occur where insufficient land is available for the waste to be applied at rates that do not exceed crop N needs. Significant reductions in N losses to the environment could be made through improvements in animal waste management. Fertilizer N also could be used more effectively if the N value of animal wastes were known more reliably and these wastes were applied more accurately.

Scientific investigations and practical experience show that the key to the critical challenge of increasing both NUE and crop productivity simultaneously is improving both the management of N and the management of the crop or cropping system to which the N is applied. These are essential to meet the challenge of feeding an increasing population while reducing possible adverse impacts on the environment. Increased education, greater adoption of modern management practices and technologies, and expanded research programmes to continue to improve knowledge of appropriate management and technologies will all be required.

Box 2. Nitrogen use efficiency terms and calculations

Partial factor productivity *(kg product/kg N applied)*: crop yield per unit N applied.

Agronomic efficiency *(kg product increase/kg N applied)*: crop yield increase per unit N applied.

Recovery efficiency *((fertilized crop N uptake - unfertilized crop N uptake)/N applied)*: increase in N uptake by the crop per unit N added, usually for the first crop following application and usually expressed as a percent or fraction.

Removal efficiency *(crop N removal/N applied)*: N removed by the harvested portion of the crop per unit N applied, usually expressed as a percent or fraction.

Physiological efficiency *(kg product increase/kg fertilizer N taken up)*: crop yield increase per unit fertilizer N taken up.

5. COMMITMENTS OF THE FERTILIZER INDUSTRY TO IMPROVE NITROGEN MANAGEMENT AND INCREASE NITROGEN USE EFFICIENCY

The correct decisions about which N product to apply to each crop, at what rate, what time and what place benefit farmers' incomes and minimize the environmental risks associated with insufficient, excess or untimely N supply.

To help farmers better manage N in the field, the fertilizer industry implements product stewardship principles throughout the supply chain. These include:

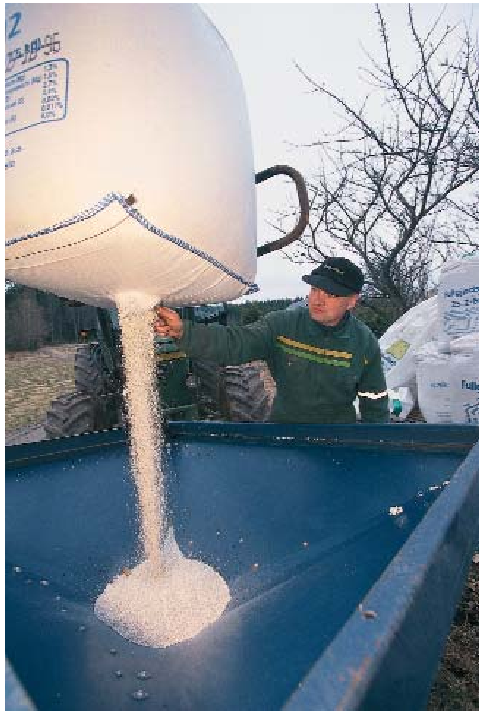
- Developing products with improved physical characteristics;
- Developing products with chemical compositions that enhance NUE;
- Making a wide range of fertilizer products available to farmers;
- Improving the supply chain;
- Developing and promoting nutrient best management practices (NBMPs);
- Measuring the performance of the recommended products and practices and
- Working with the other stakeholders and strategic partners to achieve these goals.

5.1. Developing products with improved physical characteristics

Nitrogen fertilizers must be applied evenly and at precise rates, and their spreading must be confined to the cropped area. The physical form and characteristics of fertilizer products are of major importance in achieving this.

Fertilizer products are either solid (powdered, prilled, compacted or granulated) or liquid. Today, the granular form is predominant due, partly, to its free-flowing properties (Picture 4) and absence of dust. This is achieved through the use of conditioners (anti-dust, anti-caking particle coatings or additives), which help preserve the initial physical condition of the fertilizer throughout the supply chain. Density and homogeneity of the products have been improving as well through developments in technology.

Developing physical characteristics of the products that meet the needs of various application techniques (by hand or mechanically) is critical. For instance, products with a well-controlled and specified range of granule sizes are marketed (Picture 5) to allow even application at widths of more than 28 metres using mechanical centrifugal spreaders.

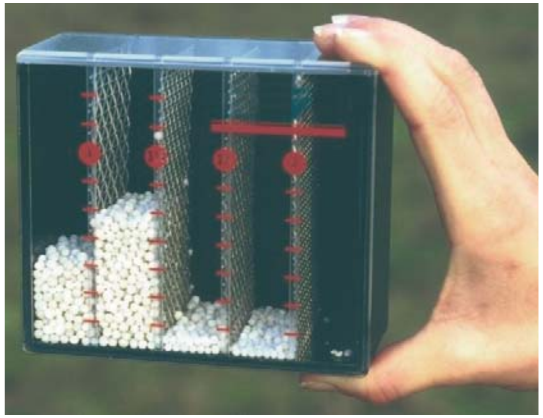


Picture 4. Free-flowing fertilizer (Credit: Yara)

Highly soluble fertilizers have also been developed to meet the technical requirements for fertigation (application of fertilizers in irrigation water).

5.2. Developing products with chemical compositions that enhance nitrogen use efficiency

Products with slow- or controlled-release characteristics are available. Slow-release products are decomposed microbially and/or by hydrolysis, while controlled-release fertilizers are coated or encapsulated products, or products with nutrients incorporated into a matrix. These two types of products extend the availability of N to the plant significantly longer than "conventional" fertilizers. Nitrogen is released progressively to match the pattern of plant



Picture 5. Granule size control with the size guide number scale (Credit: Sulky-Burel)

uptake over a defined period. A wide range of products with different release patterns is available to fit the requirements of different crops in various agro-ecological conditions. Today, these products are widely used on turf and horticultural crops. Their use on agricultural crops is often constrained by their cost. Products with prices closer to those of conventional fertilizers are being developed. This might make them more attractive for agricultural crops, in particular where it is difficult to split applications of conventional fertilizers or in environmentally sensitive areas.

Nitrogen fertilizers containing nitrification or urease inhibitors also have been developed. Nitrification inhibitors inhibit or delay the biological oxidation of ammoniacal N to nitrate N, while urease inhibitors inhibit or depress temporarily the hydrolysis of urea by the urease enzyme. These additives contribute to reduced N losses to the environment through leaching of NO_3^- or volatilization of NH_3.

5.3. Making a wide range of fertilizer products available to farmers

There are three main forms of N in manufactured fertilizers: the ammoniacal form (NH_4^+), the nitric form (NO_3^-) and the ureic form ($CO(NH_2)_2$). Nitric forms are quickly taken up by crops, but are also prone to leaching. Ammoniacal and ureic forms are susceptible to NH_3 volatilization. A range of fertilizers containing one or more of these forms is available to provide different handling, storage and agronomic characteristics (nutrient content, acidification potential, etc.). It is very important that the farmers have a large choice of fertilizer products so that they can use those that are most efficient in their site-, crop- and time-specific conditions.

In addition to straight fertilizers (containing N only), there are also compound (multi-nutrient) fertilizers with diverse nutrient ratios. A large range of formulations is available to farmers. These products contain N, P and K, but also secondary and micronutrients, as needed. By allowing balanced fertilization, they contribute to better NUE. In some countries, however, the availability of a wide range of compound fertilizers is constrained by regulatory procedures.

5.4. Improving the supply chain

It is essential that the initial quality of fertilizer products is preserved as they move through the supply chain. For instance, solid fertilizers must remain free-flowing and retain their original density, homogeneity, absence of dust and specified range of particle sizes. Necessary measures are taken during production and distribution to ensure that these properties are retained.

A specific integrated supply chain has been developed for direct application of NH_3 (a common practice in North America).

There are many countries where access to fertilizer is hampered by various barriers, in particular by weak market and transportation infrastructures, as is the case in most of Sub-Saharan Africa. Deficient infrastructures result in high fertilizer distribution costs, which are often combined with low crop prices. This makes the use of fertilizers unattractive to farmers. It is critical that policy makers are made aware of the urgent need to improve that situation by shifting from the vicious circle of poor soil fertility / low yields / rural poverty / food insecurity to a virtuous circle of soil fertility / higher yields / poverty alleviation / food security. Several initiatives are aimed at finding solutions to this major challenge. Where the policy and regulatory environment is positive, these initiatives are expected to improve the availability and affordability of fertilizers in Sub-Saharan Africa.

5.5. Developing and promoting nutrient best management practices

Several environmental and agronomic factors affect the different N loss pathways (Peoples *et al.*, 2004). The objectives of nutrient best management practices (NBMPs) are: (i) to mitigate the impact of environmental variables that result in high N losses and (ii) to promote the use of farming practices that maximize crop uptake and soil fertility and thus limit N loss to the wider environment. Depending on local agro-ecological conditions, some loss pathways may be more important than others. Nutrient best management practices should focus on reducing the main loss pathways, without increasing losses through other pathways. The gain obtained through reduction of one loss pathway should benefit the crop.

Using the right fertilizer product at the right rate, right time and right place is a basic principle for improving NUE. Simple measures such as incorporating urea into the soil or split applications of nitric fertilizer forms can significantly limit N losses. Table 2, taken from the TFI/PPI leaflet "Fertilizer Product Stewardship", gives examples of NBMPs.

It is urgent and a long-term challenge to develop NBMPs customized to specific agro-ecological conditions, and to have these NBMPs adopted by farmers. In this connection, IFA and its members (fertilizer companies, industry-sponsored institutes and associations) promote NBMPs, with particular attention to N fertilizer management. They have developed guidelines tailored to specific national or regional requirements.

In addition, experimental work and development of N management tools is underway to facilitate implementation of NBMPs at the local or even at the farm and field levels. Field trials and assessment of recommendations for fertilizer use by crop are carried out at the local level. In the main agricultural areas, networks of agri-business retailers/outlets have been established to provide sound agronomic advice and services to farmers together with the supply of the necessary agricultural inputs (Picture 6). Services can include soil testing (Picture 7), spreading equipment (Picture 8), etc.

Table 2. Examples of nutrient best management practices

NBMP category	NBMP examples
Right product *Match fertilizer type to crop needs*	▪ Soil testing ▪ Balanced fertilization (N, P, K, secondary and micronutrients) ▪ Enhanced-efficiency fertilizers ▪ Nutrient management planning *Select appropriate fertilizer and on-farm nutrient sources for the cropping system*
Right rate *Match amount of fertilizer to crop needs*	▪ Soil testing ▪ Yield goal analysis ▪ Crop removal balance ▪ Nutrient management planning ▪ Plant tissue analysis ▪ Applicator calibration ▪ Crop inspection ▪ Record keeping ▪ Variable rate application technology ▪ Site-specific management
Right time *Make nutrients available when crops need them*	▪ Application timing ▪ Slow- and controlled-released fertilizers ▪ Nitrification and urease inhibitors ▪ Fertilizer product choice
Right place *Keep nutrients where crops can use them*	▪ Application method ▪ Incorporation of fertilizer ▪ Buffer strips ▪ Conservation tillage ▪ Cover cropping

Picture 6a.

Picture 6b.

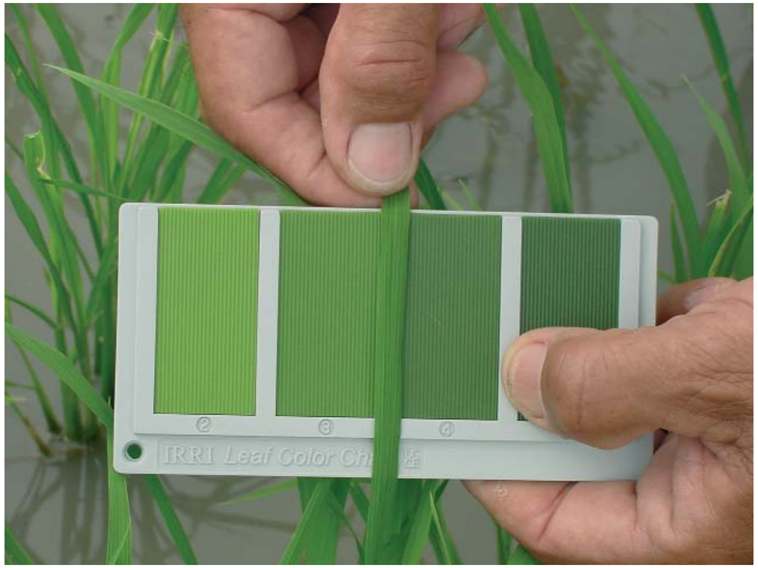
Pictures 6a and 6b. Providing agro-services together with inputs: the “Hariyali Kisaan Bazar” initiative in India (Credit: DCM Shriram Consolidated Ltd)

Picture 7. Soil sampling (Credit: INRA - LDAR Laon)

Picture 8. Spreader calibration (Credit: DSM Agro France)

In order to improve NUE, it is also key to develop and disseminate tools for assessing the nutritional status of growing crops. Tools for both high-tech and low-tech farming benefit all categories from small-scale subsistence farmers to large-scale commercial farmers. Such tools are essentially aimed at:

- Measuring the N concentration in plant sap or plant tissue, either in a laboratory, or directly in the field using a test kit;
- Measuring the chlorophyll content in the leaves using a simple leaf colour chart (Picture 9) or a chlorophyll meter (Picture 10). The chlorophyll content is a good indicator of the N status of the crop;

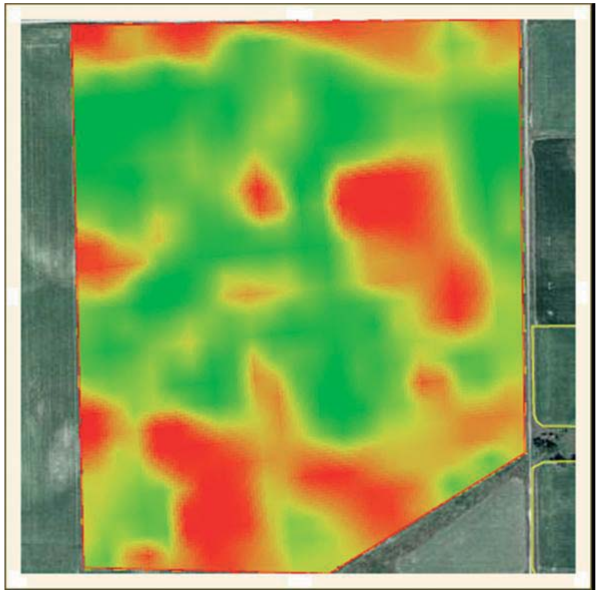


Picture 9. Leaf colour chart (Credit: ©International Rice Research Institute)

- Measuring the crop canopy's reflectance through remote sensing. These tools allow “precision” farming, with variable fertilizer application rates within a field. Depending on the instruments, they can be held by farmers on foot, mounted on tractors, or involve aircraft or satellite views (Picture 11).

Whether simple or sophisticated, these tools allow significant improvement to NUE through better assessment of actual N crop requirements and adjustment of timing and rate of N fertilizer applications.

Picture 10. Chlorophyll meter (Credit: Yara)



Picture 11. Satellite image of a plant canopy’s reflectance (Credit: The Mosaic Company)

Software packages also are available to help farmers track the N budget in each field and to make appropriate decisions for N applications.

5.6. Measuring the performance of the recommended products and practices

The last step of the product stewardship approach is to measure the performance of the recommended products and practices in delivering environmental, social and economic benefits. This must be done for all N sources and practices in order to identify their comparative advantages in given local conditions.

The best indicators for measuring this performance are water and air quality, soil fertility, food and nutrition security, human health and farmers' incomes. These indicators encompass the environmental, social and economic dimensions of sustainable agricultural development.

5.7. Working with stakeholders and strategic partners

Maximizing the benefits associated with the use of N and minimizing negative impacts require close cooperation between all stakeholders. Partnering between the fertilizer industry and the other stakeholders is particularly important to:

- Coordinate research and development efforts. More specifically, joint efforts are needed to better assess the N cycle at different scales (e.g. farm, watershed, national, continental and global levels), to better understand impacts of reactive N on both the environment and human health, to develop and promote fertilizer products and farming practices that improve NUE and, therefore, limit impacts on the environment.
- Exchange information on the state of knowledge to allow (i) faster development and adoption of products and practices that would improve NUE and (ii) appropriate policy decisions.
- Develop policies that contribute to mitigating the negative impacts of excess or insufficient reactive N, while maximizing benefits to improve world food and nutrition security.
- Develop practical solutions that will be adopted by farmers. Farmers should be involved in the identification and development of practices and policies aimed at mitigating the negative impacts of under-use, overuse or misuse of N in their farming systems.

Stakeholders should include: policy makers, scientists and extension workers, fertilizer producers and distributors, agricultural equipment firms and farmers. IFA and its members are active participants in relevant fora such as the International Nitrogen Initiative (INI), the Scientific Committee on Problems of the Environment (SCOPE) and the United Nations Environment Program (UNEP), among others.

6. CONCLUSION

There is still a great deal of uncertainty regarding the N cycle. Significant research is needed to better quantify, from the farm to the global level, fluxes among the different reactive N forms; between reactive N and the N_2 pool; and among the different compartments of the planet (biosphere, atmosphere, hydroshpere and pedosphere). Improving management of reactive N definitively requires a better understanding of the N cycle.

The agricultural N cycle cannot be separated from the global N cycle since agriculture operates within nature and cannot be completely contained as can production in a factory. There will always be N flows between the agricultural system and the wider environment. It is the responsibility of farmers, advisors, scientists and the industry to minimize losses of reactive N compounds, and to enhance NUE in crop production. However, inevitable losses and the need to increase world agricultural production make the use of manufactured N fertilizer together with biological N fixation essential for sustainable development.

The efficiency of fertilizer N use varies between countries and farming systems. Progress is being achieved in most developed countries, while NUE is still declining (or plateauing in the best case scenario) in most developing countries. As a result, average NUE at the global level has remained almost stable over the past two decades. Given these major regional differences, assessments and recommendations should be site-specific rather than global. Particular attention should be paid to the situation in developing countries, where crop productivity and/or NUE are, in general, comparatively low.

Development of practices, tools and products for more precise (site- and time-specific) N management is expected to result in gains in NUE in the medium term at the global level. These products and practices should make it possible to partly fill the gap between current relatively low NUE levels observed in farmers' fields and results achieved in well-managed research plots. Because more than half of world N consumption takes place in Asia, where farms are predominantly small-scale, the main challenge remains the transfer of improved practices to hundreds of millions of farmers. At the same time, financial support provided to governmental extension services is rapidly declining throughout the world. Partnerships involving governments, the industry and other stakeholders will be required to fill this gap.

REFERENCES

Aitkin, D.W. 2003. Transitioning to a renewable energy future; ISES White Paper. International Solar Energy Society, Freiburg, Germany. http://whitepaper.ises.org.

Balasubramanian, V., B. Alves, M. Aulakh, M. Bekunda, Z. Cai, L. Drinkwater, D. Mugendi, C. Van Kessel and O. Oenema. 2004. Crop, environmental, and management factors affecting nitrogen use efficiency. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Bruinsma, J. (Ed.). 2003. World agriculture: towards 2015/2030. An FAO perspective. Food and Agriculture Organization of the United Nations, Rome, Italy.

Bumb, B. and C. Baanante. 1996. The role of fertilizer in sustaining food security and protecting the environment to 2020. Discussion paper No. 17. International Food Policy Research Institute, Washington, DC, USA.

Cassman, K.G., A. Dobermann and D.T. Waters. 2002. Agroecosystems, nitrogen use efficiency, and nitrogen management. Ambio 31(2), 132-140.

Dobermann, A. and K.G. Cassman. 2004a. Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security? *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Dobermann, A. and K.G. Cassman. 2004b. Predicting global N fertilizer requirement from trends in N efficiency of major crops, countries, and regions. *In* Programme and Abstracts of the Third International Nitrogen Conference, Nanjing, China, 12-16 October 2004. Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China.

EEA. 1998. Europe's environment: the second assessment. European Environment Agency, Copenhagen, Denmark.

EEA. 2002. Environmental signals 2002. Benchmarking the millennium. European Environment Agency, Copenhagen, Denmark.

EEA. 2005. ETC-ACC air emissions spreadsheet for indicators 2005. European Environment Agency, Copenhagen, Denmark. http://dataservice.eea.europa.eu

FAO. 2000. Fertilizer requirements in 2015 and 2030. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2002. World agriculture: towards 2015/2030 - summary report. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2004. The state of food insecurity in the world. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2006. FAOSTAT agricultural database. Food and Agriculture Organization of the United Nations, Rome, Italy. http://faostat.fao.org.

FAO/IFA. 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land. Food and Agriculture Organization of the United Nations, Rome, Italy, and International Fertilizer Industry Association, Paris, France.

Fixen, P.E. and F.B. West. 2002. Nitrogen fertilizers… meeting contemporary challenges. Ambio 31(2),169-176.

Fixen, P.E., J. Jin, K.N. Tiwari and M.D. Stauffer. 2005. Capitalizing on multi-element interactions through balanced nutrition… a pathway to improve nitrogen use efficiency in China, India, and North America. Science of China: 48(Supp.):780-790.

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling and B.J. Cosby. 2003. The nitrogen cascade. BioScience 53 (4), 341-356.

Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asner, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, J.H. Porter, A.R. Townsend and C.J. Vörösmarty. 2004. Nitrogen cycles: past, present, and future. Biogeochemistry 70, 153-226.

Giller, K.E., P. Chalk, A. Dobermann, L. Hammond, P. Heffer, J.K. Ladha, P. Nyamudeza, L. Maene, H. Ssali and J. Freney. 2004. Emerging technologies to increase the efficiency of use of fertilizer nitrogen. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Heffer, P. and M. Prud'homme. 2006. Medium-term outlook for global fertilizer demand, supply and trade, 2006-2010; summary report. International Fertilizer Industry Association, Paris, France.
www.fertilizer.org/ifa/publicat/PDF/2006_cape_town_ifa_summary.pdf

Hofman, G. and O. Van Cleemput. 2004. Soil and plant nitrogen. International Fertilizer Industry Association, Paris, France.

IFA. 2006. IFADATA Statistics from 1973/74 to 2003/04. International Fertilizer Industry Association, Paris, France.
www.fertilizer.org/ifa/statistics/IFADATA/summary.asp

IPCC. 2001. Climate change 2001: the scientific basis. Intergovernmental Panel of Climate Change, Geneva, Switzerland.

Krupnik, T.J., J. Six, J.K. Ladha, M.J. Paine and C. van Kessel. 2004. An assessment of fertilizer nitrogen recovery efficiency by grain crops. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Leifert, C. and M.H. Golden. 2000. A re-evaluation of the beneficial and other effects of dietary nitrate. Proceedings No. 456. International Fertiliser Society, York, UK.

L'hirondel, J. and J.L. L'hirondel. 2002. Nitrate and man; toxic, harmless or beneficial. CABI Publishing, Oxon, UK.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Scenarios: Findings of the scenarios working group. Island Press, Washington, DC, USA.

Mosier, A. and C. Kroeze. 1998. A new approach to estimate emissions of nitrous oxide from agriculture and its implications to the global nitrous oxide budget. IGACtivities Newsletter No. 12, March 1998. http://www.igac.noaa.gov

Mosier A.R., J.K. Syers and J.R. Freney. 2004. Nitrogen fertilizer: an essential component of increased food, feed and fiber production. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Oenema, O. and S. Tamminga. 2004. Nitrogen management in animal production systems. In Programme and Abstracts of the Third International Nitrogen Conference, Nanjing, China, 12-16 October 2004. Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China.

Peoples, M.B., J.F. Angus, A.D. Swan, B.S. Dear, H. Hauggaard-Nielsen, E.S. Jensen, M.H. Ryan and J.M. Virgona. 2004a. Nitrogen dynamics in legume-based pasture systems. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Peoples, M.B., E.W. Boyer, K.W.T. Goulding, P. Heffer, V.A. Ochwoh, B. Vanlauwe, S. Wood, K. Yagi and O. Van Cleemput. 2004b. Pathways of nitrogen loss and their impacts on human health and the environment. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Perlack, R.D., L.L. Wright, A. Turhollow, R.L. Graham, B. Stokes and D.C. Erbach. 2005. Biomass as feedstocks for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Dept. of Energy and USDA. Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Rosegrant, M.W., M.S. Paisner, S. Meijer and J. Witcover. 2001. Global food projections to 2020 - emerging trends and alternative futures. International Food Policy Research Institute, Washington, DC, USA.

Smeets, E., A. Faaij and I. Lewandowski. 2004. A quick scan of global bio-energy potentials to 2050. Report NWS-E-2004-109. Copernicus Institute, Utrecht University, The Netherlands.

Smil, V. 1999. Nitrogen in crop production: an account of global flows. Global Biogeochemical Cycles 13 (2), 647-662.

UNIFA. 2005. Agricultural production and mineral nitrogen fertilizer deliveries. UNIFA, Paris, France.

U.S. Census Bureau. 2005. World population information. Population Division, International Programs Center, U.S. Census Bureau, Washington, DC, USA. www.census.gov/ipc/www/world.html (Consulted 13 January 2006)

US-EPA. 2006: Global anthropogenic non-CO_2 greenhouse gas emissions: 1990-2020. United States Environmental Protection Agency, Washington, DC, USA.

USDA-ERS. 2004. USDA agricultural baseline projections to 2013. Economic Research Service, United States Department of Agriculture, Washington, DC, USA.

WHO. 1970. European standards for drinking water, 2nd ed. World Health Organization, Geneva, Switzerland.

WHO. 1993. Guidelines for drinking-water quality, 2nd ed. World Health Organization, Geneva, Switzerland.

Wood, S., J. Henao and M. Rosegrant. 2004. The role of nitrogen in sustaining food production and estimating future nitrogen fertilizer needs to meet food demand. *In* SCOPE 65: Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment, edited by A.R. Mosier, J.K. Syers and J.R. Freney. Island Press, Washington, DC, USA.

Zhang, F., J. Wang and W. Zhang. 2006. Sustainable use of plant nutrients in China. *In* Proceedings of the IFA Agriculture Conference “Optimizing Resource Use Efficiency for Sustainable Intensification of Agriculture”, 27 February-2 March 2006, Kunming, China. International Fertilizer Industry Association, Paris, France.

ANNEX 1. GREENHOUSE GAS EMISSIONS AND THE KYOTO PROTOCOL

Both inorganic and organic reactive N compounds play a role in contributing to and reducing greenhouse gases (GHGs) in the atmosphere. A better understanding of the GHG risks and benefits of these compounds as they are generated and transformed throughout the plant nutrient production and use life-cycle is critical.

Of the reactive N compounds, only N_2O is classified as a GHG.

There is currently some debate whether NH_3 may play a role in global warming. The evidence is both incomplete and inconclusive and, in some cases, indicates that NH_3 is as likely to result in global cooling as in warming.

Production of most N fertilizers generates both CO_2 and N_2O. The use of fertilizers enhances the removal of CO_2 from the atmosphere by plants, but also produces emissions of N_2O.

Greenhouse gases and fertilizer production

Greenhouse gases are generated during production of NH_3 and nitric acid (HNO_3):

- Ammonia production is inherently energy intensive, producing CO_2 from both process (feedstock) and fuel sources. According to the last IFA benchmarking exercise, the CO_2 generation from NH_3 production ranges from 1.52 to 3.06 tonnes of CO_2 per tonne of NH_3 produced for the 66 participating ammonia plants. On average, one third of the CO_2 emissions is from fuel burning and two-thirds are process emissions from the use of hydrocarbon feedstock. Many facilities utilize all or part of the process generated CO_2 for urea production. Globally, some 28% of produced CO_2 is captured for urea production (PSI, 2005). Carbon dioxide generated by the fertilizer industry is also sold to other industries: e.g. to the oil/gas industry (for injection in wells) or to the beverage industry.
- Nitric acid is produced by fertilizer companies for the manufacture of ammonium nitrate (AN) and related products. As HNO_3 is produced from NH_3, N_2O is emitted proportional to the amount of NH_3 used or the amount of HNO_3 produced. Concentration of N_2O is also influenced by

engineering factors such as burner design, burner temperature, pressure, catalyst age, etc.

Picture 12. Nitrogen fertilizer plant (Credit: Yara)

What is the industry doing?

Energy efficiency in the manufacture of NH_3 has improved dramatically over the past century as shown in Figure 14. Reduction of CO_2 emissions is closely linked to the evolution of energy use efficiency and has made tremendous progress during the same period.

As the theoretical minimum is approached by modern manufacturing facilities, further gains in energy efficiency become more difficult to attain. Nevertheless, further improvements continue to be achieved. Canadian studies indicate that, over the past decade, energy intensity of N fertilizer production improved by some 13% (CIPEC, 2004), and that energy intensities for NH_3 production were between 29.7 and 37.5 gigajoules per tonne (GJ/t) of NH_3. At the global level, according to the last IFA benchmarking exercise, the energy consumption figures range from 28.0 to 53.0 GJ/t NH_3 for the 66 participating ammonia plants.

Nitric acid production is often a component of integrated fertilizer manufacturing plants. New technologies are under development to control N_2O emissions from this process. The average emission per plant in Europe is 6 kg N_2O per tonne of HNO_3 produced, equivalent, in GHG terms, to 1.9 tonnes of CO_2.

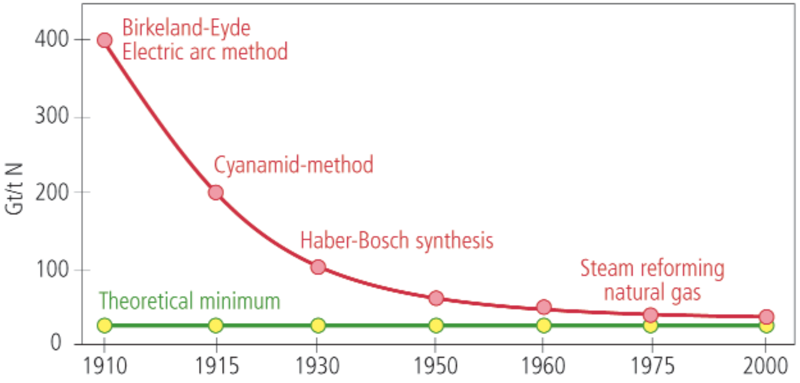


Figure 14. Design energy consumption trends in ammonia plants (Adapted from Anundskas, 2000)

The N_2O emission rate from HNO_3 plants varies as follows:

- Atmospheric pressure plants: 5 kg N_2O/t HNO_3
- Medium-pressure plants (3-7 bar): 7 kg N_2O/t HNO_3
- High-pressure plants (>8 bar): 5-9 kg N_2O/t HNO_3

Greenhouse gases and fertilizer use

The use of N fertilizer results in both the generation and the removal of GHGs:

- Fertilizer use and N_2O emissions

  The primary GHG emission from N fertilizer application is N_2O. The Intergovernmental Panel on Climate Change (IPCC) has set an emission factor of 1.25% of the fertilizer applied being lost as N_2O. However, research from a number of sources suggests that a lower factor is appropriate: 1.0% in the FAO/IFA report on nitrogenous gas emissions from agricultural land (2001), and as low as 0.5% in some other studies (Burton and Grant, 2002). It is becoming abundantly clear that emission rates are dependent on a host of regional factors. Certain management practices to reduce emissions may apply generally from one region to another.

- Fertilizer use and carbon (C) sequestration

  It is well established that various agricultural management practices can be used to increase C sequestration in soils, thereby reducing GHG emissions.

  It is worth noting that CO_2 used for urea production is released in the field after hydrolysis of urea, giving no benefit to urea vs. other N fertilizers from a life-cycle approach in terms of CO_2 emissions.

What is the industry doing?

In addition to the research mentioned above, the fertilizer industry publishes (i) best available techniques for the manufacturing of fertilizers, which involve the use of proven technologies and methods of operation in order to prevent or minimize emissions to the environment and (ii) best nutrient management practices recommending optimal timing (e.g. through split application or use of more efficient fertilizers) and site-specific use, in order to minimize the amount of NO_3^- available for conversion to N_2O and subsequent losses to the atmosphere.

References

Anundskas, A. (Yara International, Norway). 2000. Personal communication.

Burton, D.L. and C.A. Grant. 2002. Reducing nitrous oxide emissions through the use of fertilizer management technologies. Canadian Fertilizer Institute, Ottawa, Canada.

CIPEC. 2004. Canadian Industry Program for Energy Conservation; 2003/2004 Annual Report. CIPEC, Ottawa, Canada. http://oee.nrcan.gc.ca/publications/infosource/pub/cipec/AnnualReport03-04

FAO/IFA. 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land. Food and Agriculture Organization of the United Nations, Rome, Italy, and International Fertilizer Industry Association, Paris, France.

PSI. 2005. Energy efficiency and CO_2 emissions: benchmarking of CFI ammonia producers, 2000-2002; General edition, March 2005. Plant Surveys International, Petersburg, Virginia, USA.

ANNEX 2. INTERNATIONAL DEVELOPMENTS

The impact of N on the environment and human health is becoming an increasingly important issue in international scientific and policy arenas. The following are worth mentioning:

- 1978: The Scientific Committee on Problems of the Environment (SCOPE) and the United Nations Environment Program (UNEP) jointly established an International Nitrogen Unit.
- 1980: Concern about the quality of drinking water resulted in an EU directive recommending a maximum level of 50 mg NO_3^- per litre of drinking water.
- Mid-1980s: The World Health Organization (WHO) followed the EU's position, and recommended a maximum limit of 50 mg NO_3^- per litre of drinking water.
- 1991: The EU adopted the Nitrates Directive concerning the protection of waters against pollution caused by NO_3^- from agricultural sources.
- 1997: The Kyoto Protocol included N_2O in its list of GHGs requiring reduction.
- 1998: The issue of N in the environment came to the fore when SCOPE organized the first International Nitrogen Conference, held in The Netherlands.
- 1999: The United Nations Economic Commission for Europe (UNECE) tackled NH_3 emissions by including them in the Convention on Long-range Transboundary Air Pollution, in the context of the issue of acid rain.
- 2001: The second International Nitrogen Conference was held in the USA. It recommended the creation of the International Nitrogen Initiative (INI).
- 2002: Establishment of the INI, an inter-disciplinary group that examines the impact of anthropogenic activities on the N cycle at the global and regional scales.
- 2003: UNEP raised public interest in the issue through a section on the N cascade in its Global Environment Outlook Yearbook.
- 2004: The third International Nitrogen Conference was held in China. The “Nanjing Declaration” was adopted on that occasion. The Declaration calls for better management of the global N cycle, in order to optimize the

benefits associated with the use of reactive N, and minimize its unwanted impacts. The Declaration has been submitted to UNEP for consideration.

- 2006: UNEP organized a meeting in March to exchange information on how reactive N is currently regulated in some countries and regions, discuss whether policy makers should consider regulating reactive N in a global context, and what instruments might be needed.
- 2007: The fourth International Nitrogen Conference will take place in October in Brazil.

Involvement of the fertilizer industry

- The fertilizer industry was represented in the three International Nitrogen Conferences and in the 2006 UNEP meeting.
- The fertilizer industry is represented on the advisory body of the INI.
- IFA participated actively and financially in the organization of the SCOPE workshop on N fertilizer held in 2004 in Uganda. The outcomes of the workshop, which provides an in-depth scientific review of the contribution and impacts of N fertilizer use on food production and the environment, were published by SCOPE just prior to the third International Nitrogen Conference.
- In 2004, IFA established a Task Force on Enhanced-Efficiency Fertilizers and it organized an international workshop on enhanced-efficiency fertilizers in June 2005. The workshop looked at the contribution of slow- and controlled-release fertilizers, and of urease and nitrification inhibitors to the challenge of improving N use efficiency. Proceedings are available on-line at www.fertilizer.org/ifa/news/ 2005_17.asp
- In 2005, IFA established a Task Force on Reactive Nitrogen, which is responsible for raising the awareness of the IFA members on the reactive N issue. The task force drafted this publication, as well as a public summary.
- In 2006, IFA established a Task Force on Fertilizer Best Management Practices. It is responsible for promoting best management practices, with particular attention to N management in developing countries.
- In 2007, IFA will organize an international workshop on fertilizer best management practices. The workshop is aimed at exchanging information on experiences, defining the general principles of fertilizer best management practices and the strategy for their wider adoption, defining the role of the fertilizer industry in developing and promoting fertilizer best management practices, and identifying priority areas for action.
- In 2007, IFA will launch a web portal on fertilizer best management practices at www.SustainableCropNutrition.info.