Challenges and opportunities facing animal agriculture: Optimizing nitrogen management in the atmosphere and biosphere of the Earth[1]

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ABSTRACT: Humans need food. Humans use energy. Production of food and combustion of fossil fuels increase concentrations of reactive nitrogen in the atmosphere, soils, and surface and ground waters of the Earth. These increases are caused in part by agricultural practices aimed primarily at increasing food production: the use of synthetic nitrogen fertilizers, widespread planting of N-fixing legumes, increased demand for animal protein in human diets, and increased use of fossil fuels. The world's crops, forests, and fisheries respond to reactive nitrogen (defined in the body of this article) enrichment with some positive benefits (such as increased food, feed, timber, and fish production) and some negative consequences (including acidification and eutrophication of aquatic and terrestrial ecosystems, decreased biodiversity, increased regional haze, global warming, and such human health impacts as nitrate contamination of drinking water and increased pulmonary and cardiac disease caused by exposure to toxic ozone and fine particulate matter).

So far, most pollution abatement strategies have aimed at resolving one or another air or water pollution problem in which various oxidized, reduced, and organic forms of reactive nitrogen play an important part. The time has come to consider more fully integrated strategies by which reactive nitrogen management practices can be optimized to increase agricultural, forest, and fish production while decreasing nitrogen-induced soil, air, and water pollution.

Contemporary challenges and opportunities facing animal agriculture in the United States today include joining with the U.S. Environmental Protection Agency, animal industry, university, and other scientists and policy makers in making realistic assessments of actual positive and negative impacts of reactive nitrogen emissions and leaching from animal agriculture and developing practical (economic) guidelines and strategies for the following: a) improving nitrogen conversion efficiency in poultry, swine, beef/dairy, and fish production, b) minimizing reactive nitrogen losses from manures, c) conserving and reusing reactive nitrogen and other valuable nutrients in animal wastes, d) developing more cost-effective horizontally and vertically integrated systems of animal production and manure management through production and marketing of value-added products, and e) minimizing use of fossil fuels in agriculture.

Key Words: Air Pollution, Ammonia, Emission, Environmental Impact, Nitrogen Cycle, Nutrient Management, Water Pollution

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Introduction

This review paper was prepared with the following general purposes in mind.

1. Explore some general features of the nitrogen cycle of the Earth and how this cycle is being altered by humans in their quest for food, energy, and other amenities of modern life.
2. Explain how contemporary changes in animal agriculture are increasing the circulation of biologically active and chemically or physically reactive nitrogen (**Nr**)[3] among the atmosphere, soils, forests,

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[3] The term *reactive nitrogen* as used in this paper includes all biologically active, photochemically reactive, and radiatively active (climate changing) nitrogen compounds in the atmosphere and biosphere of the Earth. Thus, Nr includes a) inorganic reduced forms of N (such as NH_3, NH_4^+), b) inorganic oxidized forms of N (such as NO_x, HNO_3, N_2O, NO_3^-, NO_2^-), and c) organic compounds (such as urea, uric acid, amino acids, amines, proteins, nucleic acids).

fish, surface and ground waters, and oceans of the Earth—mainly through atmospheric emissions of ammonia from animal feeding operations and oxides of nitrogen from fossil fuels used in transport of feed grains, animals, manures, and marketable food products.

3. Consider how these increases in Nr circulation are causing some positive benefits for agriculture, forestry, and fisheries while also causing some negative impacts on air and water quality, human health, ecosystem productivity, and other air and water quality-related values.
4. Explore the potential for enterprising farmers and ranchers to join with other experts in animal nutrition, agricultural engineering, atmospheric chemistry and meteorology, and agricultural economics in universities, government agencies, and the private sector in developing alternative technologies by which value-added products can be produced from animal manures and food-processing wastes to increase the profitability of animal agriculture.
5. Provide justification for adopting a Total Reactive Nitrogen Approach (Total Nr Approach) rather than continuing to try to decrease emissions of oxidized and reduced forms of nitrogen separately.
6. Propose a Concept of Optimum Nitrogen Management for Society in North America, Europe, and Asia.
7. Encourage animal scientists to continue their education about optimizing Nr management in food production, energy use, and environmental protection (see lists of additional references at the end of this article that pertain to continuing education).

The Nitrogen Cycle of the Earth

Nitrogen is the very stuff of life. It constitutes a major part of the nucleic acids that determine the genetic character of all living things and the enzyme proteins that drive the metabolic machinery of every living cell. Triple-bonded gaseous dinitrogen (N_2) makes up nearly 80% of the total mass of the Earth's atmosphere. But none of this huge reservoir of N is biologically available. Before N can be used by most plants, animals, insects, and microorganisms, the triple bonds between gaseous N_2 molecules must be broken and the resulting single N atoms must be bonded chemically with one or more of three other essential nutrient elements—oxygen and/or hydrogen through N-fixation processes and carbon through N-assimilation processes.

Breaking the triple bonds between gaseous dinitrogen molecules is an energy-requiring reaction. In nature, fixation of N_2 is accomplished mainly by certain unique microorganisms that have developed the special metabolic machinery necessary to produce biologically active *reduced* forms of nitrogen, such as ammonia, amines, and amino acids, which are the structural constituents of proteins and nucleic acids. These specialized organisms include a few free-living bacteria and blue-green algae, and also certain symbiotic bacteria that have developed special metabolic relationships with the roots of leguminous crop plants such as soybeans, clover, and N-fixing trees such as alder. Oxidative fixation of gaseous N_2 also occurs in nature, but only in such high-temperature natural processes as lightning strikes, volcanic eruptions, and wild fires that lead to production and atmospheric emissions of nitrogen oxides: NO, NO_2, HNO_3, NO_3^-, N_2O, HONO, N_2O_5, PAN (peroxyacetyl nitrate), and PPN (peroxypropionyl nitrate).

In the prehuman world, biological nitrogen fixation (**BNF**) was the dominant means by which new reactive nitrogen was made available to living organisms. The total amount of Nr that circulated naturally among various compartments of the atmosphere and the biosphere of the Earth was quite small. Thus, the awesome biodiversity and intricate webs of relationships we find in nature evolved in part as a result of intensive competition among many different life forms—most of them growing under Nr-limited conditions.

Human Alteration of the Nitrogen Cycle

Gradually during the past two centuries, and more markedly during the last few decades, various human activities have been adding larger and larger amounts of Nr to terrestrial and aquatic ecosystems and thus augmenting the natural circulation of Nr through the atmosphere and the biosphere of the Earth. As described more fully by Vitousek et al. (1997) and Galloway (1998), two major human imperatives have driven these recent changes in the N cycle of the Earth:

1. The need for food to sustain growing numbers of people all over the world. This has been achieved primarily through an increased use of synthetic Nr fertilizers, widespread planting of N-fixing legumes, and increases in animal agriculture to meet growing demand for animal protein in human diets.
2. The seemingly insatiable human appetite for energy and materials with which to create and transport many of the goods, services, and other amenities of modern human life.

Figure 1 shows some important aspects of our historical understanding of nitrogen: its inclusion as an element in the periodic table in 1789, its significance as an essential element for life processes in 1840, the discovery of biological nitrogen fixation in 1890, the invention of the Haber-Bosch process for making synthetic nitrogen fertilizers in 1913, and the relationship between this series of scientific discoveries and the spectacular growth in the human population during the twentieth century (Galloway and Cowling, 2002; Galloway et al., 2002).

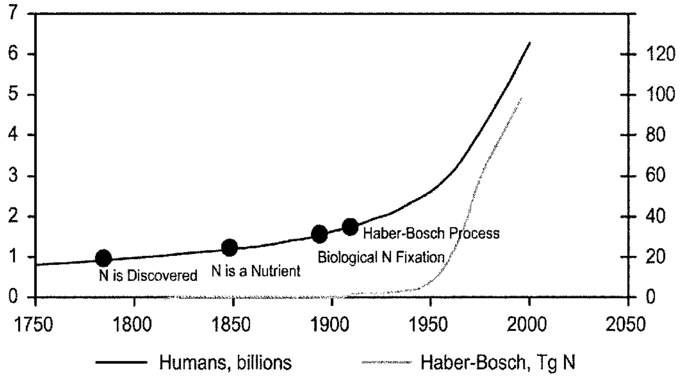

Figure 1. The history of nitrogen and human population. Note the global human population trend from 1860 to 2000 (billions of people, left axis). This figure is adapted from Galloway and Cowling (2002).

Figure 2 shows the timelines of change in Nr added to global circulation as synthetic Nr fertilizers through the Haber-Bosch process and other forms of Nr added through widespread planting of N-fixing legumes and combustion of fossil fuels. Over the last 150 yr, the rate of addition and partial accumulation of anthropogenic Nr has increased from about 15 to about 160 Tg N/yr. Please note that both synthetic Nr fertilizers and N-fixing legumes are adding about six times more biologically active, photochemically reactive, and radiatively active (climate altering) N to global circulation than is the total worldwide combustion of fossil fuels. An important part of this Nr enrichment is caused by contemporary changes in animal agriculture. There also have been significant changes in fluxes of Nr to the atmosphere and oceans and some human-induced changes in biological denitrification as well.

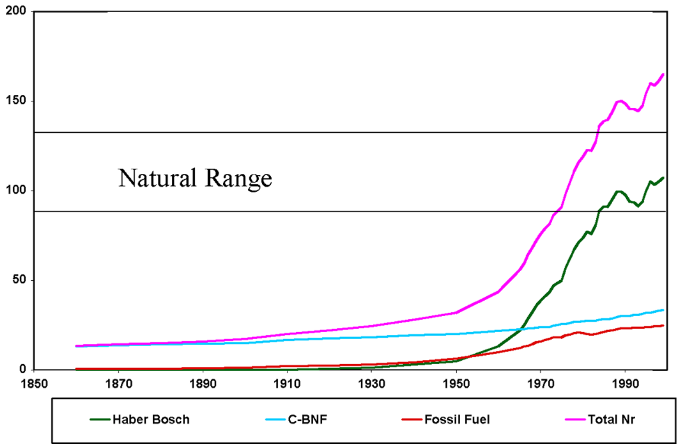

Figure 2. Human alteration of the nitrogen cycle of the Earth. Note rates of Nr creation (in teragrams of Nr per year) through various human activities: "Haber Bosch" = synthetic NH_3 formation through the Haber-Bosch process, mainly for production of commercial fertilizers; "C-BNF" = Nr creation through widespread cultivation of N-fixing legumes, paddy rice, and sugar cane; and "Fossil Fuel" = Nr creation through oxidative fixation of N during combustion of fossil fuels. "Total Nr" is the sum of all three major anthropogenic sources ("Haber Bosch" + "C-BNF" + "Fossil Fuel"). "Natural Range" refers to the approximate global biological fixation of Nr in the prehuman terrestrial environment. This figure is adapted from Galloway and Cowling (2002).

Table 1. Agricultural and forestry activities that augment the nitrogen cycle of the Earth

Activity
• Harvesting of wild animals and fish
• Burning of natural vegetation to make way for agriculture
• Harvesting and utilization of timber
• Production of major food crops (especially cereal grains, beans, and potatoes, and various fruit, nut, and vegetable crops)
• Husbandry of domestic meat-producing and milk-producing animals (especially poultry, swine, beef cattle, sheep, dairy cattle, and goats)
• Land application of animal manures
• Combustion of crop and logging residues
• Widespread cultivation of nitrogen-fixing legumes
• Increased production and use of synthetic N fertilizers
• Increased fish- and shellfish farming in ponds, lakes, streams, rivers, estuaries, and ocean waters

As indicated in Tables 1 and 2, many agricultural and forestry activities—and many more industrial, commercial, and military activities—have increased and are continuing to augment the N cycle of the Earth. In fact, the total amount of Nr circulating through the

Table 2. Industrial, commercial, and military activities that augment the nitrogen cycle of the Earth

Activity
• Combustion of fossil fuels in:
· Domestic space and water heating devices
· Firing of pottery and manufacture of glass and ceramics
· Smelting of metal-containing ores and processing of metals
· Production of cement
· Power plants for generation of electricity
· Small and large industrial and commercial boilers
· Construction and earth-moving equipment
· Farm tractors and implements
· Industrial machines powered by internal combustion engines
· Transportation vehicles (including cars, trucks, railroads, ships, aircraft, and space vehicles)
• Production and refining of oil for liquid fuels and production of petrochemicals
• Other chemical industries
• Pulp and paper manufacturing
• Disposal of urban wastes in landfills
• Incineration of household and municipal wastes (including garbage, food-processing wastes, waste paper, plastics, medical wastes, and construction and demolition debris)
• Operation of sanitary sewers and sewage treatment plants
• Land applications of sewage sludges
• Use of explosives in peace and war

atmosphere and the biosphere of the Earth is now unprecedented in human history and is increasing rapidly, especially in Asia.

The Changing Structure and Globalization of Animal Agriculture

During the last several decades, three dramatic changes in the structure and organization of animal agriculture have occurred in many parts of the world. They are all resulting in an increased need for optimization of nutrient management plans for animal agriculture—especially as they pertain to handling and processing of manures and other food-processing wastes and use of fossil fuels. These three major changes are as follows. *Intensification*: development of increasingly large confined animal-feeding operations, in which hundreds or even thousands of live animals are reared in open feedlots or enclosed housing units. *Decoupling*: physical separation of the land area where the feed grains and other forage products are produced and the site on which the food animals are fed and reared. *Regionalization and globalization of markets*: huge increases in the distance of transport of both feed grains and other forages and marketable meat, eggs, dairy, and fish food products.

Driving these three trends are powerful economic forces, namely, economies of scale, efficiencies of specialization, cheap food and transportation policies, and the pressures of global competitiveness. These forces have stimulated development of highly specialized, large-scale, vertically integrated livestock, poultry, and fish rearing, processing, and marketing systems. These systems are designed to maximize conversion of feed grains and other forages into the specialized and uniform swine, beef/dairy, poultry, and fish food products demanded by price-conscious consumers. Unfortunately, as discussed more fully below, economic efficiency, often made possible by increased use of energy in the form of fossil fuels, frequently leads to some nutrient-use inefficiencies and largely unforeseen detrimental environmental consequences.

The end result of *intensification* in confined animal-feeding operations is to concentrate animal rearing and manure production on a very small land area. Here the dominant tendency is to regard manure as an “unpleasant waste material that must be disposed of by the least costly methods available.” The traditional alternative, of course, was to return the residual nutrients in manure to the land where the feed grain or other forages were produced. A second alternative—and a so far much less widely accepted one—is to regard manure and other animal-harvesting wastes as “valuable natural resources” from which additional products can be produced and sold at a profit.

The end result of *decoupling* is to separate the land area where feed grains and forages are produced from the sites where the food animals are reared. In traditional mixed farming operations, this distance was a few hundred meters and the same farmer who raised the livestock or fish also raised the feed grain or other forages on the same land base. With today’s modern specialized farming operations, however, many swine, beef/dairy, poultry, and fish farmers are specialists who, more often than not, produce little if any of the feed grains or other forages on their own land. In recent decades, both specialization among food animal producers and further decoupling of animal agriculture has been facilitated by enterprising integrators. These entrepreneurs are guided by knowledgeable animal-production scientists, agricultural engineers, economists, and extension agents in the universities and private industry. As a result, contracts are developed that link farmers; integrators; and meat, egg, dairy, and fish product-processing and -marketing companies. The integrators provide engineering designs for new types of housing or other animal-rearing and manure-handling equipment and facilities, genetically improved young animals, feed rations specifically designed to maximize weight gain per unit of feed or forage consumed, prescriptions for feeding and watering rates, disease management counsel and advice, and, most importantly, a guaranteed price to farmers who deliver finished food animals to a specific food-processing plant on a specified time schedule. The processing and marketing companies then deliver uniform, high-quality food products attractively packaged to meet the demands of price-conscious consumers.

The end-result of *regionalization and globalization of markets* is to greatly enlarge the geographical scale of production and marketing operations in the food-animal industry. Often there are remarkably long distances of transport between the places where the feed grains and forages are produced, the food animals are reared, the plant where the animals are slaughtered and processed, and the grocery stores and restaurants where the food products are delivered to consumers. Fossil fuel energy is consumed, and oxidized forms of Nr are produced at every step in these often far-flung transportation processes. Powerful economic forces also are at work at all stages in these production, transport, and marketing systems. Thus high-quality and very uniform animal food products are delivered to sometimes distant markets at remarkably low consumer prices.

The major problem with all three of these contemporary trends is the lack of economic or other incentives for recycling—returning the valuable nutrients in animal wastes back to the land that was used to produce the feed. As a result, much of the Nr and other valuable nutrients in animal manures and food-processing wastes is “disposed of by least cost methods,” that is, released into the environment in the vicinity of the animal-rearing and food-processing facilities. The released substances most often are volatile ammonia, amines, and nitrogen oxides that are emitted to the atmosphere where they form ammonium nitrate or ammonium sulfate aerosols or leach into ground water.

Table 3. Beneficial and detrimental effects on society induced by increased circulation of reactive nitrogen (Nr) in the atmosphere and biosphere of the Earth

Direct effects of Nr on humans

1. Increased yields and nutritional quality of foods needed to meet dietary requirements and food preferences for increasing human populations all over the world
2. Respiratory and cardiac disease in people caused by exposure to high concentrations of:
    - Ozone
    - Other photochemical oxidants
    - Fine aerosol particles
    - (On rare occasions) direct toxicity of NO_2
3. Nitrate and nitrite contamination of drinking water
4. Blooms of toxic algae and decreased swimability of water bodies

Direct effects of Nr on ecosystems

1. Increased productivity of Nr-limited crops, forests, and natural ecosystems
2. Enhanced overall soil productivity through greater microbial activity and improved soil health
3. Ozone damage to crops, forests, and natural ecosystems and predisposition to attack by pathogens and insects
4. Acidification effects on forests, soils, ground waters, and aquatic ecosystems
5. Eutrophication of freshwater lakes and coastal ecosystems
6. Stimulation of algal growth and productivity in coastal waters, with possible effects on coastal food webs and fisheries including decreased concentrations of dissolved oxygen (hypoxia and anoxia), decline or elimination of submerged aquatic vegetation, promotion of certain algal species that are harmful because they produce toxins
7. Nitrogen saturation of soils in forests, grasslands, and other natural areas
8. Loss of biodiversity through loss of N-poor habitats in terrestrial and aquatic ecosystems and shifts in ecosystems to domination by nitrophilic species of plants
9. Changes in abundance of beneficial soil organisms that alter ecosystem functions
10. Carbon sequestration can be increased in ecosystems where Nr is limiting, with possible amelioration of CO_2 accumulation and resulting climate change

Indirect effects of Nr on other societal values

1. Increased wealth and well-being of human populations in many parts of the world
2. Increased yield per unit of cultivated land has made it possible to preserve marginal and forested land for ecosystem maintenance
3. Significant changes in patterns of land use
4. Regional hazes that decrease visibility at scenic vistas and airports
5. Odor problems associated with animal agriculture
6. Damage to useful materials and cultural artifacts by ozone, other oxidants, and acid deposition
7. Depletion of stratospheric ozone by N_2O emissions
8. Global climate change induced by emissions of N_2O and formation of tropospheric ozone
9. Long-distance transport of Nr, which causes harmful effects in regions or countries distant from emission sources and/or increased background concentrations of ozone and fine particulate matter
10. Increased cost of societal regulations necessary to avoid the detrimental effects of Nr

All of the volatile inorganic and organic forms of Nr are carried by wind and deposited in precipitation or as dry deposition of gases and aerosols wherever the wind blows—sometimes in the vicinity of the animal-rearing or -processing facilities rather than returned to the sometimes distant land where the feed was produced. In North America, highly competitive demand for low-cost animal food products and absence of significant economic penalties or regulations prohibiting improper animal waste management have been major impediments to optimizing management of Nr and other nutrients in animal agriculture.

Beneficial and Detrimental Effects of Nr Emissions from Animal Agriculture

Every increment in the amount of total Nr circulating through the atmosphere, soils, sediments, standing biomass, and oceans of the Earth brings a corresponding potential increase in the productivity of agriculture, forestry, and aquatic ecosystems (see the beneficial effects listed in Table 3). As shown in Figure 3, however, each increment of Nr beyond a certain optimal range brings an increased likelihood of at least some among a long list of Nr-induced detrimental effects on society (see also the detrimental effects listed in Table 3).

Unfortunately, many voluntary recommended management practices or mandated rules and regulations have been focused around one specific air- or water-pollution problem at a time. In some cases, decisions about abatement strategies for one problem have interfered with measures intended to resolve another or have affected some other social or economic aspect of society. For example, regulations in the Netherlands that require farmers to inject animal manures into soil increase the likelihood of nitrate contamination of drinking water (Erisman and Monteny, 1998). Also, decreases in emissions of nitrogen oxides have sometimes led to increases in ambient concentrations of ozone in the central core of some cities in North America (USEPA, 1997). In the United States, "non-discharge" permits intended to prevent pollution of surface and ground waters by confined animal-feeding operations ignored volatile emissions of ammonia and amines from

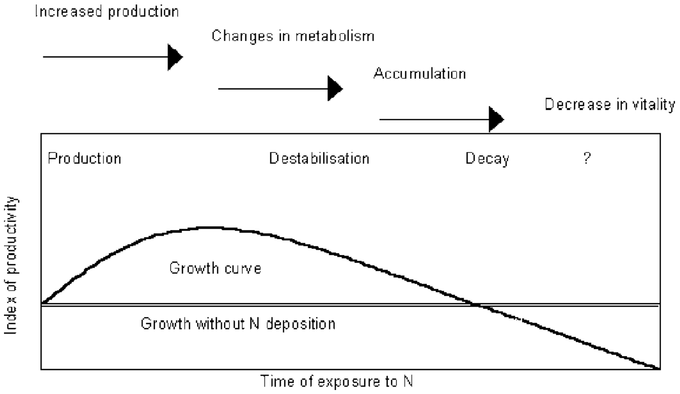

Figure 3. Hypothetical growth curve showing the productivity of terrestrial and aquatic ecosystems receiving different loadings of total reactive nitrogen. This figure is slightly modified from the original curve developed by Per Gundersen of the Laboratory of Environmental Sciences and Ecology, Technical University of Denmark, Lyngby, Denmark (Gundersen, 1992).

animal-housing units and manure-handling and storage systems.

Realistic possibilities exist for developing more rational and more fully integrated strategies and tactics for enhancing the efficiency of Nr use in animal agriculture while decreasing the occurrence of detrimental effects such as those listed in Table 3.

Potential for Decreasing the Detrimental Impacts of Animal Agriculture on the Environment

Economically viable technologies are being developed for conservation and profitable reuse of nitrogen and the other valuable nutrients in animal wastes. These wastes are of three general types: 1) urine and feces in animal manures, 2) waste streams from processing plants that include feathers, bones, blood, offal, and other unused or underused portions of the harvested food animals, and 3) carcasses of animals that become diseased, die of known or unknown causes, or are slaughtered deliberately to avoid the spread of dread diseases such as foot and mouth disease or mad cow disease. The valuable nutrients in all three of these waste streams can be recovered and reused both safely and economically. The main approaches to this goal are as follows:

1. Direct application of animal manures to land used for producing grain or other forages.
2. Conversion of nutrients in the waste streams into marketable fertilizer products for reuse in crop, forest, or fish production.
3. Production of energy or other value-added products (especially high-value end products) for use in industry and commerce.
4. Denitrification back to biologically inactive atmospheric N_2.

As suggested by Sheffield (2000) and Cowling et al. (2002), the value-added end products that could be produced by converting the valuable nutrients in animal wastes into saleable commodities include the following:

1. Ammonia, urea, or uric acid captured from animal-rearing facilities for sale as commercial feedstocks or reagents for the chemical, fertilizer, nylon, electrical utility, or other industries.
2. Energy in the form of methane, biogas, diesel fuel, or electricity for direct on-farm purposes.
3. Electricity for sale through co-generation contracts with public utilities.
4. Synthetic growth media for high-value ornamental plants or soil amendments for residential or commercial landscaping purposes.
5. Nitrogen- and phosphorus-rich fertilizer materials for direct application to crops, such as corn, cotton, and sweet potatoes, or to fast-growing pine and/or hardwood plantations.
6. Fertilizer materials for greenhouse production of floral crops and other ornamental plants.
7. Feed materials and nutritional supplements to enhance feed conversion efficiency in fish, poultry, and livestock production. These supplements could include dehydrated duckweed, high-protein fish meal, and amino acid and vitamin supplements.
8. Protein products for veterinary applications in aquaculture, poultry, and livestock industries, including nutritional enzymes, edible vaccines, and antiviral proteins, such as interferon.
9. Protein products for industrial applications, including industrial antibodies and enzymes used in detergents, recycling, and in processing of pulp, paper, textile, and chemical products.
10. Production of high-value protein-based biomaterials, including adhesives, fibers such as silk, optically active films, and other biopolymers or plastics.
11. Food materials for companion animals.
12. Higher-value foods for human consumption including wholesome fish, vegetable, fruit, and dairy products.

Another possibility is direct conversion of Nr into nonreactive nitrogen gas (N_2) that can be returned to the atmosphere. This additional option would avoid detrimental public health, ecological, or other environmental impacts but would provide no direct income to farmers or waste-processing industries to sustain the conversion processes. Nevertheless, these direct denitrification processes should be evaluated to compare their economic and other costs and benefits with production and marketing of various saleable end products and/or viable combinations of end products.

In attempting to decrease air emissions of ammonia, it is important to recognize that most of the Nr excreted by swine and by beef/dairy cattle is in the urine; and that urease, the enzyme that converts urea to ammonia, is mainly in the feces (Kaspers et al., 2000). Thus, manure-handling systems for swine and cattle that separate liquid from solid wastes will have substantially lower ammonia emission rates.

It is also important to recognize that urea conversion and ammonia volatilization continue from the time of excretion by the animals, during manure storage and treatment, and before and after possible land application. In the well-ventilated barn and lagoon and sprayfield system widely used in swine production in North Carolina, for example, about 40% of the ammonia is lost through the ventilation system of the houses, about 30% from the surface of the lagoons, and about 30% during and after application onto the spray fields and from decomposing bales of Bermuda hay left at the sides of the spray fields (there is little market demand for Bermuda hay) (Aneja et al., 2000; 2001).

The most serious obstacles to overcoming the consequences of intensification, decoupling, and regionalization and globalization of markets in the food animal industry are as follows: 1) the distances over which feed grains are transported before delivery to animal rearing facilities—sometimes in another state or even a far-distant country; 2) reluctance and doubt among farmers, integrators, and their extension-service and private consultant advisors about the technical and/or economic feasibility of alternative systems for nutrient management, animal production, and waste utilization; 3) lack of convenient and reliable processes for combining manure-based fertilizer products with synthetic chemical fertilizer in intensively managed cropping systems.

Especially as confined animal-feeding operations become more common, conversion of animal manures and animal-processing waste materials into value-added products for profitable sale is a logical strategy. It will simultaneously achieve several desirable environmental, public health, and economic goals:

- Recovery and reuse of the nutrient resources in the waste streams.
- Decrease or elimination of detrimental effects on public health and environment.
- Development of profitable private-sector business and employment opportunities.
- Enhancement of the economic and environmental sustainability and the social acceptability of food animal industries and the social, economic, and environmental well-being of the rural and near-urban communities in which these facilities are located.
- Decrease in regulatory costs (education, permitting, inspection, and enforcement) associated with current waste-processing systems.

Justification for a "Total Reactive Nitrogen Approach" in Air- and Water-Quality Management

So far, most of the voluntary recommended management practices and the mandated rules and regulations for management of Nr have been developed and administered separately. Moreover, most of the guidance for prevention of water discharges from confined animal-feeding operations have been developed and administered without regard for the associated air emissions of volatile ammonia and amines. Air emissions of NO_x were first regulated because NO_x is an important precursor of ozone and later because it also contributes to acidification of soils and surface waters. Similarly, air emissions of ammonia first became a pollutant of concern because ammonia contributes to acidification processes. All forms of Nr participate in a variety of chemical and physical transformations in the atmosphere. As indicated in Table 3, they also can have a long series of beneficial and detrimental biological effects once they are deposited in terrestrial and aquatic ecosystems.

Thus, the time has come to develop and implement a Total Reactive Nitrogen Approach (Total Nr Approach) rather than continue to consider nitrogen-oxide pollution and ammonia pollution in isolation from each other and from other aspects of air quality management. As discussed more fully by Grennfelt et al. (1994), a Total Nr Approach is especially important in the context of current discussions about multiple-pollutant/multiple-effects perspectives in air- and water-quality management and should become integral parts of Nr management in both crop and animal agriculture and in forestry, fisheries, and watershed management. A Total Nr Approach is firmly grounded in the following biological principles (Linder, 1995; Gundersen, 1992; Vitousek et al., 1997):

1. All oxidized, reduced, and carbon-bound (organic) forms of Nr are biologically active. When transferred into ecosystems in less than optimal amounts, they increase the productivity of the system (see the ascending part of the curve in Figure 3 and the beneficial effects listed in Table 3).
2. When applied in more than optimal amounts, however, all biologically active forms of N contribute to the wide variety of Nr-induced pollution problems listed in Table 3 (see the descending part of the curve in Figure 3).
3. The biologically important oxidized forms of Nr include NO, NO_2, HNO_3, NO^-, HONO, N_2O_5, PAN (peroxyacetyl nitrate), and PPN (peroxypropionyl nitrate). Biologically important reduced forms of Nr include gaseous ammonia, dissolved and aerosol forms of ammonium ion, and a wide variety of organic Nr compounds, including urea, uric acid, amines, and amino acids.
4. The total supply of Nr in terrestrial and aquatic ecosystems is a complex function of the following:
   a) The amounts of nonreactive N_2 gas removed from the atmosphere by free-living N-fixing microorganisms in soils and by symbiotic N-fixing microorganisms in the roots of some crop plants and a few species of forest trees.

   b) The amounts of oxidized and reduced forms of Nr in the soil solution and in decomposing organic matter in soil.
   c) The total amounts of Nr transferred from the atmosphere into ecosystems by wet and dry deposition processes.
   d) The amounts of Nr applied to land as synthetic fertilizers and animal wastes.
   e) The runoff of Nr compounds from the land to surface waters.
   f) Microbial processes in soils that transform oxidized, reduced, and organic forms of Nr and release them back into the atmosphere as NO, NO_2, NO_3^-, HNO_3, N_2O, and N_2.
5. Although there are transitory differences in rates of uptake and assimilation of oxidized, reduced, and organic forms of Nr by different organisms, both oxidized and reduced forms of Nr ultimately have substantially similar influences on the general productivity of the terrestrial, aquatic, and livestock-dominated ecosystems in which they are assimilated. This is true because at least one or another (and sometimes many) of the various plants, animals, microbes, and insects in terrestrial or aquatic ecosystems take up all oxidized, reduced, and organic forms of Nr.

After initial uptake and assimilation, these various forms of Nr are readily transformed and exchanged with other organisms and compartments within a given landscape or watershed so that all Nr molecules have a series of cascading biological effects within the natural or managed ecosystems in which they are incorporated (Galloway, 1998; Vitousek et al., 1997).

These linkages and biological principles provide strong justification for adoption and implementation of a Total Nr Approach in air quality management. As discussed below, they also set the stage for development of a Concept of Optimum Nitrogen Management for Society.

Development of a Concept of Optimum Nr Management for Society

In his most famous book, *Future Shock*, Toffler (1970) identified three types of futures that he believed innovative democratic societies should consider very carefully. *Probable futures*—hopes and aspirations of society that are largely an extension of a business-as-usual sense of what the future might hold. *Possible futures*—exploration of all possible outcomes that a given society might wish to consider as possibilities for its future. *Preferable futures*—optimum outcomes that probably can be achieved only as a result of focused and well-disciplined efforts to fulfill mutually agreed upon goals and dreams that are consonant with the natural and human resources available to society.

In evaluating alternatives about the management of air and water quality in the context of other important societal goals, enlightened societies will want to consider Toffler's suggestions and thus go beyond "business-as-usual" perspectives, to look earnestly at a wide range of "possibilities," and to work hard to define and implement "preferable" options that are both prudent and realistic for the long-term as well as for the short-term futures of society. In thinking further about how so-called preferable futures might be identified in the case of Nr, we found valuable theoretical guidance in the Theory of Optimum Nutrition developed by Ingestad (1987). We also found valuable practical guidance in the Gundersen (1992) concept of Optimum Ecosystem Productivity.

Ingestad (1987) first theorized, and later established experimentally, that maximum growth and production of both agricultural crops and forest trees can be obtained by optimizing, in all stages of growth and development, the availability of each of the 16 nutrient elements that are required for the growth of plants (and by inference, the 27 elements that are essential for animals). Since Nr is the essential nutrient that most often limits growth of crops and forests, Ingestad reasoned and expressed his experimental findings as ratios between the amounts of each of the other essential nutrients and the amount of Nr available to the organism of interest. Thus, Ingestad confirmed the central role that Nr plays in determining the health and productivity of plants. He also established procedures for determining optimum amounts of Nr and other nutrients to ensure maximum growth. Similar principles also apply to the growth and development of livestock and fish.

Gundersen (1992) extended these ideas to show that Nr plays a central role in determining the productivity and stability of whole ecosystems. A very slightly modified version of the Gundersen (1992) original graph is shown in Figure 3. This figure shows that growth within a whole ecosystem receiving no significant input of Nr from the atmosphere or other external sources has a relatively constant "index of productivity," that an ecosystem receiving moderate amounts of added Nr responds by increasing the productivity of the whole system, that there is a maximum (optimal) productivity for any given living system; and that additions of more than optimal amounts of Nr eventually cause destabilization, decrease in vitality, and eventual decline in the productivity of the whole ecosystem.

The Gundersen (1992) concept of Optimum Productivity applies to many different types of land use (and surely also to livestock-feeding operations). Thus, each type of land use follows its own unique (but similarly shaped) productivity/Nr-input curve—with productivity first increasing, then going through a maximum, and eventually decreasing with increasing inputs of total Nr. This idea is illustrated in Figure 4, where ecosystem-productivity/Nr-input relationships are shown for five general types of land use in the Netherlands.

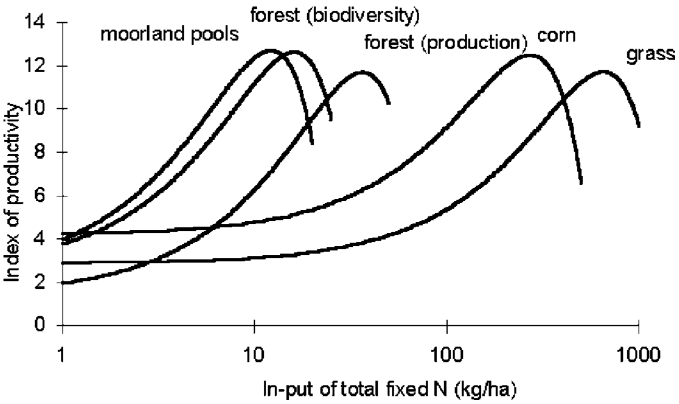

Figure 4. Hypothetical growth curves for five types of terrestrial ecosystems: natural moorland pools, forest biodiversity, timber production, and production of corn and grass crops. This figure is adapted from the concept of Optimum Ecosystem Productivity advanced by Gundersen (1992) (see Figure 3).

Please note that each particular type of land use showed its own relationship between the productivity of the system and the total Nr input to that system from all sources. As discussed earlier, these sources include wet and dry deposition from the atmosphere (in all cases), applications of Nr in synthetic fertilizers (where applied), and application of animal manures and other Nr-containing waste materials (where applied). It is possible to further extend this idea of a curvilinear relationship between the productivity of various uses of land and inputs of Nr and to adapt and apply the idea in making nutrient management recommendations for various crops, species of livestock, and thus for the whole of society.

In essence, a curvilinear relationship of the general form shown in Figures 3 and 4 can be defined between what might be called an Index of Societal Sustainability and the total amount of Nr transferred from the atmosphere and other external sources into different geographical areas within a given society. This proposed Index of Societal Sustainability would be analogous for a whole community or society with the Gundersen (1992) Index of Productivity for a whole ecosystem.

The construction of such a sustainability index will require the development of a series of land-use-specific and food-animal-specific productivity/Nr-input curves for each type of natural resource use that is commonplace within society. From the Nr-input values for maximum productivity for each natural resource system, it should be possible to determine an approximate total–Nr-input ceiling for maximum productivity of each type and locality of resource use. These values then can be used as inputs to gridded atmospheric-source/resource-use receptor models to establish area-specific and animal agriculture–specific input ceilings for each major source of Nr. With this information as background, it then should be possible for each community, state, or country to determine (negotiate) an optimum total Nr loading for the various sectors within society and then to consider alternative measures by which to adjust nutrient input rates accordingly. Thus, each particular geographical and economic sector within a given community, state, or country could adjust its own imports and exports of Nr and thus do its part toward achieving a *preferable total nutrient management system within a more sustainable and equitable society*.

In an attempt to illustrate how this proposed concept could be used, the following suggestions are advanced. First, quantitatively defensible productivity/Nr-input curves should be developed for each type of natural resource use on the basis of both experimental data and observations of real-world production systems. Within each locality or grid square within a given community, a selection should be made of the types of land use that should be considered most limiting or most significant economically, socially, aesthetically, and so on. These choices should be made very carefully because the land use– and area-specific Nr input ceilings and corresponding emissions ceilings will be determined using receptor modeling.

After the emissions ceilings have been determined, comparisons must be made between actual emissions and the calculated emissions ceilings for each locality or grid square. If actual emissions are lower than the calculated optimum, then some increase in Nr emissions could be considered, so long as the allowed increase in emissions does not lead to exceedances of the optimum Nr loads in other grid squares. This means, in agricultural areas, for example, that additional animal manure or synthetic Nr fertilizers could be applied to increase crop production. If actual emissions exceed the calculated optimum, however, then decreases in emissions should be undertaken. The total Nr emissions ceiling can be achieved by decreasing the amounts of reduced Nr compounds emitted or by decreasing amounts of oxidized Nr compounds, or both.

If it appears that the Nr emissions ceilings are so low that it will not be economically feasible to meet them, the target position on the optimum curve should at least be shifted in the direction of optimum Nr loading. If the optimum loading is exceeded, then hard choices will need to be made between economical interests and ecological interests. In this way, the Concept of Optimum Nitrogen Management for Society provides a tool for visualizing the consequences of economically determined and ecologically determined futures. The advantage of this concept is that the measures needed to achieve optimum Nr deposition can be chosen as a trade-off between policies and procedures designed to decrease or increase inputs of Nr, depending on what is economically feasible, socially acceptable, and environmentally sound in the short and the long run.

This Concept of Optimum Nitrogen Management for Society has been applied in a pilot case study of ammonia emissions in the province of Friesland (Erisman and van Egmond, 1997) using ammonia-emissions ceilings and maximum Nr-application rates for several municipalities in the Netherlands (Erisman et al., 1996). Portions of the concept, especially those dealing with spatial planning as a tool for decreasing Nr loads in nature areas, are also discussed by Bleeker and Erisman (1998) and most recently by Erisman et al. (2001).

Further development and especially implementation of the Concept of Optimum Nr Management for Society will require substantially increased knowledge of the growth, development, sustainability, and possibilities or realities of detrimental effects on various ecosystems and other values related to air quality and water-quality (Erisman et al., 2001). Adoption and implementation also will require substantially increased understanding and a more widely shared sense of ecological bioethics within farming, forestry, industrial, regulatory, and political communities. Various aspects and implications of some of these ideas are further discussed by Leopold (1968), Brundtland (1987), Potter (1988), and Cowling and Nilsson (1995).

Science and Policy Implications

Contemporary changes in animal agriculture are increasing the circulation of reactive nitrogen (Nr) in the environment, which creates some positive benefits for agriculture and forestry, while also causing negative impacts on air and water quality, human health, and ecosystems. In most ecosystems, the result of increased loads of Nr will be substantially the same whether Nr emissions occur as oxidized, reduced, or organic forms. Instead of dealing with different forms of Nr separately, the Total Reactive Nitrogen Approach is justified. The Concept of Optimum Nr Management for Society is also proposed. Implementation will require determination of deposition and emission ceilings for each type of land use. Alternatives by which to adjust Nr loadings then can be considered. This will facilitate decisions by which various sectors of society can adjust their emissions of total Nr, and so do their part toward achieving a preferable total Nr emissions load within a more sustainable society.

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