Challenges and opportunities facing animal agriculture: Optimizing nutrient 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 biologically active nitrogen (BAN) 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 – use of synthetic nitrogen (N) 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 N enrichment with some positive benefits (e.g., increased food, feed, timber, and fish production) and some negative consequences (e.g., 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 oxidized or reduced forms of N play an important part. The time has come to consider more fully integrated strategies by which N management practices can be optimized to increase agricultural, forest, and fish production while decreasing N-induced soil-, air-, and water pollution.

Contemporary challenges and opportunities facing animal agriculture in the United States today include joining with EPA, animal industry, university, and other scientists and policy makers in: 1) making realistic assessments of actual positive and negative impacts of N emissions from animal agriculture, and 2) developing practical (economic) guidelines and strategies for: a) improving nutrient conversion efficiency in poultry, egg, swine, cattle, dairy,

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and fish production, b) minimizing N and phosphorus (P) losses from manures, c) conserving and reusing N 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 waste-conversion products, and e) minimizing use of fossil fuels in agriculture.

Key words: Air and Water Pollution, Ammonia Emissions, Environmental Impacts, Nitrogen Cycle, Nitrogen Pollution, Nutrient Management.

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) among the atmosphere, soils, forests, fish, surface and ground waters, and oceans of the earth – mainly through atmospheric emissions of ammonia from confined animal feeding operations and oxides of nitrogen from the fossil fuels used in transport of feed grains, finished animals, 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 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 N management in food production, energy use, and environmental protection.

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 dinitrogen gas (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 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 – 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^-, HONO, N_2O_5, PAN (peroxyacetyl nitrate), and PPN (peroxypropionyl nitrate).

In the pre-human world, biological nitrogen fixation (BNF) was the dominant means by which new reactive nitrogen (Nr) 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 as a result of intensive competition among many different life forms – most of them growing under nitrogen-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
   a) Increased use of synthetic N fertilizers,
   b) Widespread planting of N-fixing legumes,
   c) Increases in animal agriculture to meet growing demand for animal protein in human diets, and
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 the history of human understanding of nitrogen – its discovery 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 among this series of scientific discoveries and the spectacular growth in the human population of the earth during the 20th Century.

Figure 2 shows the timelines of change in Nr added to global circulation as synthetic N fertilizers through the Haber-Bosch process and other forms of Nr added through widespread planting of nitrogen-fixing legumes and combustion of fossil fuels. Over the last 150 years, the rate of addition and partial accumulation of anthropogenic Nr has increased from about 10 to 140 Tg N/yr. Please note that both synthetic N fertilizers and legumes are adding more biologically active and chemically and physically reactive N (Nr) to global circulation than 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.

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 atmosphere and the biosphere of the earth is now unprecedented in human history and 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 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 include:

1) Intensification – development of increasingly large confined animal feeding operations in which hundreds or even thousands of like animals are reared in open feed lots or enclosed housing units.
2) 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,
3) Transport – huge increases in the distance of transport of both feed materials and marketable meat, eggs, milk, dairy, and fish products.

All three of these contemporary trends are driven by powerful economic forces. They include economies of scale, efficiencies of specialization, and the pressures of global competitiveness. These forces have stimulated the 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, meat, egg, dairy, 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 the 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 the manure to the land where the feed grain or other forage products 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 value added 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 hog, cattle, 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 were guided by knowledgeable animal-production scientists, agricultural engineers, economists, and extension agents in the universities and private industry. As a result, contracts were developed that linked farmers, integrators, and meat, egg, dairy, and fish product-processing and marketing companies. The integrators provided 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 *transport* 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 processing plant where the animals are slaughtered and processed, and the grocery stores and restaurants where the finished 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 and marketing systems. Thus high-quality and very uniform animal food products often are delivered to very far-distant markets at remarkably low consumer prices.

The major problem with all three of these contemporary trends in animal agriculture is lack of economic or other incentives for recycling – returning the valuable nutrients in animal waste streams back to the land that was used to produce the feed (i.e., decoupling and transport). As a result, much of the N 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, ammonium nitrate or ammonium sulfate aerosols, or nitrogen oxides that also are emitted to the atmosphere or leach into ground water.

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 – sometime in the vicinity of the animal rearing or processing facilities rather than returned to the sometimes far-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 N and other nutrients in animal agriculture.

Beneficial and Detrimental Effects of N Emissions from Animal Agriculture

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

Unfortunately, many of the 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 pollution problem 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 N 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 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 N use in animal agriculture while at the same time decreasing the frequency of occurrence of many of the detrimental effects 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, phosphorous, carbon 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. There are four main approaches to this goal:

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 production,

3) Production of energy or other value-added products (especially high-value end products) for use in industry and commerce, and/or

4) Denitrification back to biologically inactive atmospheric N_2.

As suggested by Sheffield (2000) and Cowling et al (2001), the value-added end products that could be produced by converting the valuable nutrients in animal wastes into saleable commodities include:

1) Energy in the form of methane, biogas, or electricity for direct on-farm purposes;

2) Electricity for sale through co-generation contracts with public utilities;

3) Synthetic growth media for high-value ornamental plants or soil amendments for residential or commercial landscaping purposes;

4) Nitrogen- and phosphorus-rich fertilizer materials for direct application to crops such as corn, cotton, sweet potatoes, etc., or to fast-growing pine and/or hardwood plantations;

5) Fertilizer materials for green-house production of floral crops and other ornamental plants;

6) 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;

7) Protein products for veterinary applications in aquaculture, poultry and livestock industries including nutritional enzymes, edible vaccines and anti-viral proteins such as interferon;

8) Protein products for industrial applications including industrial antibodies and enzymes used in detergents, recycling, and in processing of pulp, paper, textile, and chemical products;

9) Production of high-value protein-based biomaterials including adhesives, fibers such as silk, optically-active films, and other biopolymers or plastics;

10) Food materials for companion animals; and

11) Higher-value foods for human consumption including wholesome fish, vegetable, fruit, and dairy products.

Another possibility is direct conversion of Nr into essentially inert 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 atmospheric emissions of ammonia, it is important to recognize that most of the N excreted by swine, cattle, and poultry is in the urine of the animals; and that urease, the enzyme that converts urea to ammonia, is in the feces. Thus, manure-handling systems that separate urine from feces will have substantially lower ammonia emission rates.

It is also important to recognize that urea conversion and ammonia volatilization processes continue from the time of excretion by the animals, during manure storage and treatment, and both before and after possible land application. In the well-ventilated barn and lagoon and spray-field system widely used in swine production in North Carolina, for example, about one-third of the ammonia is lost through the ventilation system of the houses, about one-third from the surface of the lagoons, and about one-third during and after application onto the spray fields and from decomposing bales of Bermuda hay left at the sides of the spray fields because 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 transport in the food animal industry are:

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 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 and economic goals:

1) Recovery and reuse of the nutrient resources in the waste streams;
2) Decrease or elimination of detrimental effects on public health and environment;

3) Development of profitable private-sector business and employment opportunities;

4) 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; and

5) Decrease in regulatory costs (permitting, inspection, and enforcement) required by current waste processing systems.

Justification for a "Total Fixed 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. Also, most guidance for prevention of water discharges from confined animal rearing facilities 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 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") 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 nitrogen 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, 1996):

1) All oxidized, reduced, and carbon-bound (organic) forms of N are biologically available. 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.
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 N compounds including amines, amino acids, etc.
4) The total supply of Nr in terrestrial and aquatic ecosystems is a complex function of the following:
    a) The amounts of non-reactive 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 fom 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, and
    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 systems 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, 1996).

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,” Alvin Toffler (1970) identified three different types of futures, which he believed innovative democratic societies should consider very carefully:

1) “Probable futures” – hopes and aspirations of society that are largely an extension of a “business as usual” sense of what the future might hold;
2) “Possible futures” – exploration of all possible outcomes that a given society might wish to explore as possibilities for its future; and
3) “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 which are consonant with the natural and human resources available to society.

In evaluating alternative choices about 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, look earnestly at a wide range of “possibilities,” and 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 “preferable futures” might be identified in the case of Nr, we found valuable theoretical guidance in the “theory of optimum nutrition” developed by Torsten Ingestad (1987). We also found valuable practical guidance in Gundersen’s (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 growth of plants (and by inference, the 27 elements that are essential for livestock). Since N 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 growth and development of livestock and fish.

Gundersen (1992) extended these ideas to show that Nr also plays a central role in determining the productivity and stability of whole ecosystems. A very slightly modified version of Gundersen's original graph is shown in Figure 3. This figure shows that:

1) 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;"
2) An ecosystem receiving moderate amounts of added Nr responds by increasing the productivity of the whole system;
3) There is a maximum (optimal) productivity for any given living system; and
4) Additions of more than optimal amounts of Nr eventually cause destabilization, decrease in vitality, and eventual decline in the productivity of the whole ecosystem.

Gundersen's concept of "optimum productivity" applies to many different types of land use (and surely also to livestock feeding operations). Thus, each different 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.

Please note that each particular type of land use showed its own particular 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 land-use types and inputs of Nr – and to adapt and apply this general 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 Gundersen's "index of productivity" for a whole ecosystem.

Construction of such an "index of sustainability" will require the development of a series of land-use-specific and food-animal-specific productivity/Nr-input curves for each different 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 each of the various sectors within society, and then to consider various alternatives 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 in practice, 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 which should be considered most limiting or most significant economically, socially, aesthetically, etc. 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 N 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 place 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 measures designed to decrease or increase inputs of Nr, depending on what is economically feasible, socially acceptable, and environmentally sound in both 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 N 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 this proposed "Concept of Optimum Nr Management for Society” will require both substantially increased knowledge of the growth, development, sustainability, and possibilities or realities of detrimental effects on various ecosystems and other air-quality and water-quality related values (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

The major scientific and policy-relevant implications of this paper are as follows:

1) Contemporary changes in animal agriculture are increasing the circulation of biologically active and chemiaccly and physically reactive nitrogen (Nr) among the atmosphere, soils, forests, fish, surface and ground waters, and oceans of the earth – in part through water discharges but even more through atmospheric emissions of ammonia and other volatile Nr compounds from confined animal feeding operations, and also through oxides of Nr from the fossil fuels used in transport of feed grains, finished animals, and marketable food products.
2) 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.
3) Enterprising farmers, ranchers, integrators, public officials, and private-sector vendors, as well as animal nutritionists, atmospheric chemists, meteorologists, and agricultural economists in universities, government agencies, and the private sector, have much to gain by joining together in research aimed at conserving and recycling the valuable Nr and other nutrients in animal manures and food processing wastes. Converting these nutrients to value-added products that can be sold at a profit is much wiser than continuing to consider animal wastes as an "unpleasant waste to be disposed of by least-cost methods."
4) Rather than continuing to deal with oxidized and reduced forms of nitrogen separately, strong justification is provided for development of an integrated "Total Reactive Nitrogen Approach." In most terrestrial and aquatic ecosystems, the end result of continuing heavy loads of N will be substantially the same whether the airborne Nr emissions occur as Nr oxides, ammonia or ammonium Nr, or as organic forms of Nr.
5) A "Concept of Optimum Nr Management for Society" is proposed together with suggestions about practical steps for implementation. Implementation will require construction of a series of productivity/Nr-input curves for each general type of land use and then determining land-use-specific deposition ceilings and corresponding airshed-specific emissions ceilings for major sources of Nr. It then should be possible to consider various alternative measures by which to adjust area-specific Nr emissions rates and land-use-specific Nr-fertilization rates accordingly. This concept will facilitate communications which can lead to decisions

by which various sectors of society can adjust their own emissions of total Nr – and thus do their part (together with other sectors of society) toward achieving a "preferable total Nr emissions load within a more sustainable and equitable society."

6) In addition to the usual list of specific references cited in this paper, a selected bibliography of additional references is provided for those within the animal agriculture scientific and policy communities who may wish to continue their education about optimizing nitrogen management in food production, energy use, and environmental protection.

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National Atmospheric Deposition Program, Precipitation Chemistry Data for the USA, Illinois State Water Survey, University of Illinois, Champaign-Urbana, http://nadp.sws.unic.edu/

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

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

Table 2. Industrial and commercial activities that augment the nitrogen cycle of the earth

Activity
1. 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)
2. Production and refining of oil for liquid fuels and production of petrochemicals
3. Other chemical industries
4. Pulp and paper manufacturing
5. Disposal of urban wastes in land fills
6. Incineration of household and municipal wastes (including garbage, food-processing wastes, waste paper, plastics, medical wastes, and construction and demolition debris)
7. Operation of sanitary sewers and sewage treatment plants
8. Land applications of sewage sludges
9. Use of explosives in peace and war

Table 3. Detrimental effects on society induced by increased circulation of biologically available (total fixed) nitrogen in the atmosphere and biosphere of the earth[a]

Direct effects on humans
1. Respiratory 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 2. Nitrate contamination of drinking water 3. Blooms of toxic algae and decreased swimability of water bodies
Direct effects on ecosystems
4. Ozone damage to crops, forests, and natural ecosystems 5. Acidification effects on forests, soils, ground waters, and aquatic ecosystems 6. Eutrophication of freshwater lakes and coastal ecosystems 7. Nitrogen saturation of soils in forests, grasslands, and other natural areas 8. Biodiversity impacts on ecosystems
Effects on other societal values
9. Odor problems associated with animal agriculture 10. Acidification effects on monuments and engineering materials 11. Regional hazes that decrease visibility at scenic vistas and airports 12. Accumulation of hazes in arctic regions of the globe 13. Depletion of stratospheric ozone by NO_2 from high-altitude aircraft 14. Global climate change induced by emissions of N_2O 15. Increased cost of societal regulations necessary to avoid these detrimental effects

[a] All 15 of these detrimental effects can and do occur both nearby to and at long distances from emissions sources. Public concern about many of these N-induced pollutant effects is increasing in Europe, North America, Asia, and elsewhere. Thus, many societies around the world have developed recommended management practices and/or environmental protection rules, regulations, and even international treaties to prevent or mitigate one or more of these N-induced pollutant effects.

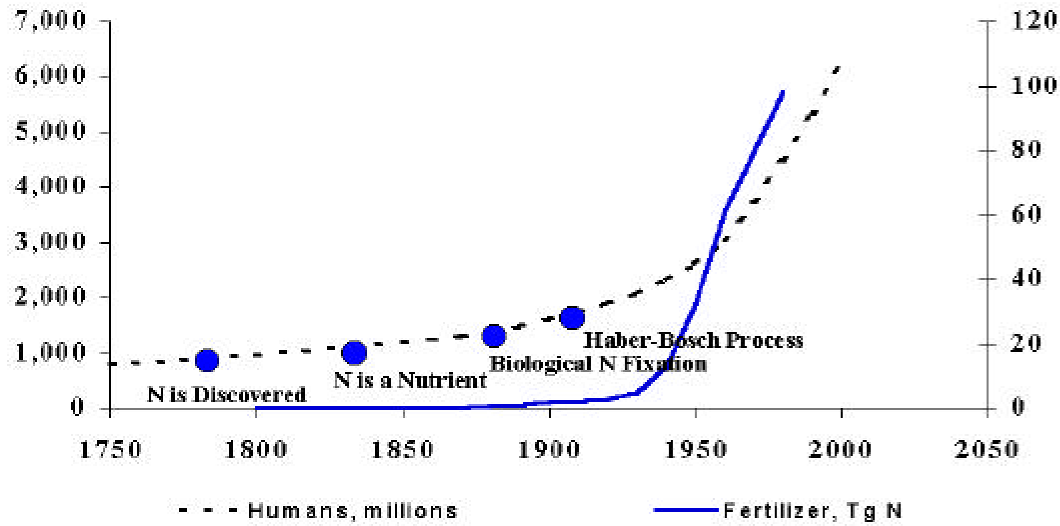

Figure 1. The history of nitrogen and the human population of the world.

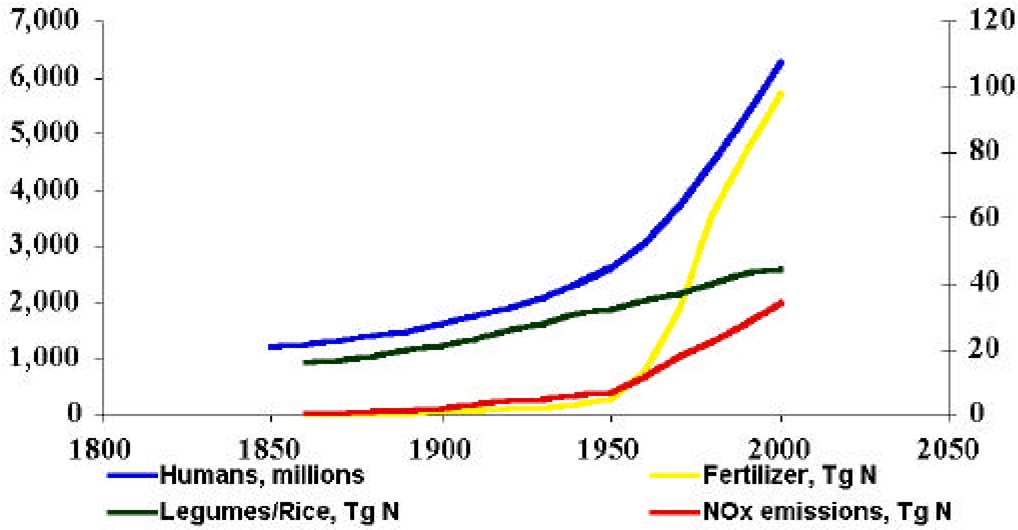

Figure 2. Human alteration of the nitrogen cycle of the Earth.

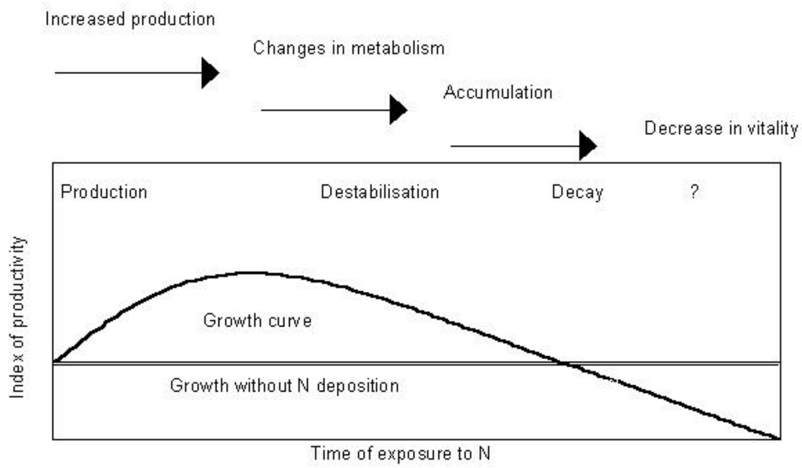

Figure 3. Hypothetical growth curve showing the productivity of terrestrial and aquatic ecosystems receiving different loadings of total reactive nitrogen. This figure is slightly modified from the original curve developed by Per Gundersen of the Laboratory of Environmental Sciences and Ecology, Technical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

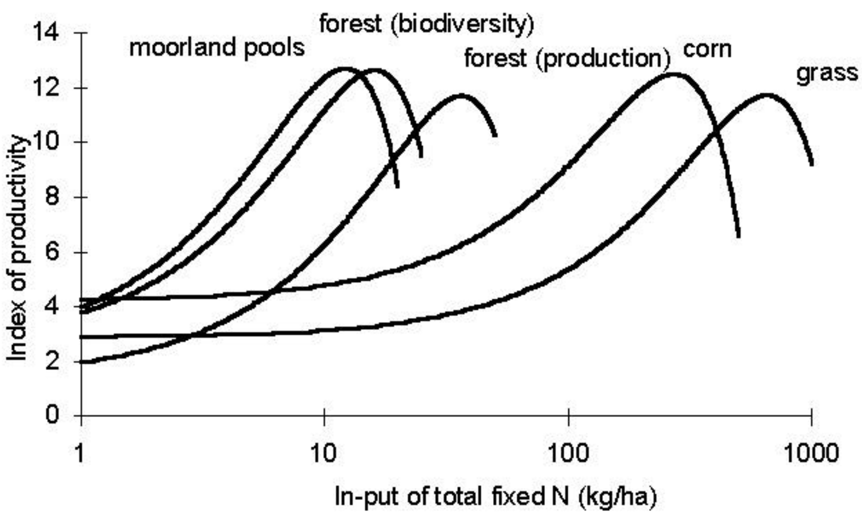

Figure 4. Hypothetical growth curves for five different types of terrestrial ecosystems -- natural moorland pools, forest biodiversity, timber production, and production of corn and grass crops. This figure was adapted from the concept of “optimum ecosystem productivity” advanced by Per Gundersen (see Figure 3).