Extended Abstract
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Long-term Nitrogen Dynamics in a Temperate Forest Ecosystem

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Environmental changes caused by humans are occurring at an accelerating rate throughout the world. Such human-accelerated environmental changes (Likens 1991) include complicated interactions among global climate change, stratospheric ozone depletion, massive land-use changes, toxification of the biosphere, infectious diseases, loss of biodiversity, and invasion of exotic species. Long-term studies, particularly in combination with experimental manipulation of entire-ecosystems, are especially helpful for discovering the rate of change and biogeochemical dynamics in complex, natural ecosystems. Long-term studies in the Hubbard Brook Experimental Forest (HBEF) are used to illustrate some of these issues for nitrogen dynamics in a temperate forest ecosystem.

The HBEF is a 3,160-ha area of northern hardwood forest in the White Mountains of Hampshire, administered by the U.S. Forest Service Northeastern Research Station. The HBEF contains 9 experimental, hydrologically-gauged watershed ecosystems. American beech (Fagus grandifolia Ehrh.), yellow birch (Betula alleghaniensis Britt.) and sugar maple (Acer saccharum Marsh.) dominate from 500 to 730 m elevation. Red spruce (Picea rubens Sarg.) balsam fir (Abies balsamea (L.) Mill) and white birch (Betula papyrifera Marsh.) largely dominate at elevations above 730 m and on north-facing slopes. The HBEF was logged intensively between 1909-1917, but there is no evidence of recent fire (Bormann et al. 1970; Whittaker et al. 1974; Bormann and Likens 1979; Davis et al. 1985; Likens and Bormann 1995). Some scattered forest damage occurred from a hurricane in 1938 (Kim 1988, Merrens 1988). Additional information about the HBEF may be found in Likens and Bormann 1995 and on the website (www.hubbardbrook.org).

Long-term research and monitoring, and large-scale, watershed-scale, experimental manipulations have been hallmarks of the Hubbard Brook Ecosystem Study since 1963 (e.g. Likens et al. 1970, Likens 1985, Likens and Bormann 1995). Based on this research and long-term monitoring, several changing dynamics of this system have been discovered: (1) The forest has stopped accumulating biomass (stopped growing!) since 1982 (Likens et al. 1994, 1998, 2002, Siccama et al. 2007). Forest biomass has been measured at the HBEF in 1965 and 1977, and at 5-yr intervals, thereafter. Initially, the forest showed significant rates of aboveground plus belowground biomass accumulation and associated element uptake (4.85 Mg/ha-yr, 1965-1977; Bormann and Likens 1979; Whittaker et al. 1974, 1979). Recent data, however, suggest that not only is this forest no longer sequestering carbon, but now it is releasing carbon to the atmosphere, primarily as a result of the effects of acid rain, climate change and disease (T. G. Siccama and J. Battles, personal communication; Siccama et al. 2007; Likens and Franklin 2009). (2) In sharp contrast to theoretical expectations, where nitrogen export in stream water would be expected to be high at the HBEF because of forest maturation and disturbance (Vitousek and Reiners 1975), or because of nitrogen saturation in forests subjected to high inputs of atmospheric nitrogen (e.g. Aber 1992), dissolved inorganic nitrogen in stream water is currently at the lowest concentration on record (e.g. Likens 2004; Fig. 1).

Because nitrogen is usually considered a limiting nutrient for such temperate forest ecosystems (e.g. Elser et al. 2007), long-term nitrogen dynamics are informative, but complicated, relative to understanding the structure, function and temporal change of these ecosystems, particularly because of external disturbances such as acid rain, deforestation, ice storms, etc. (Figs. 2 and 3). For example, disturbance by forest clear cutting causes a consistent pattern of response in the N-cycle leading to increased export of NO_3^- in stream water (e.g. Likens et al. 1970; Fig. 4).

Nitrate inputs in precipitation increased from 1964 to ~1970, then were relatively constant to ~1995 and have declined since. The pattern of streamwater NO_3 output reflects disturbance events and long-term dynamics (Fig. 5). A watershed-ecosystem balance showed net losses of ~1000 to 1300 mol N/ha-yr during 1964-1980 and net gains of ~ 400 to 600 mol N/ha-yr during 1983-2009 for Watershed 6 of the HBEF.

Experimental addition of $CaSiO_3$ (Wollastonite) to an entire watershed-ecosystem at the HBEF, in an amount approximating the Ca lost as a result of leaching from acid rain during the past 50 years (Likens et al. 1996), is beginning to show a positive response in the biota (Juice et al. 2006).

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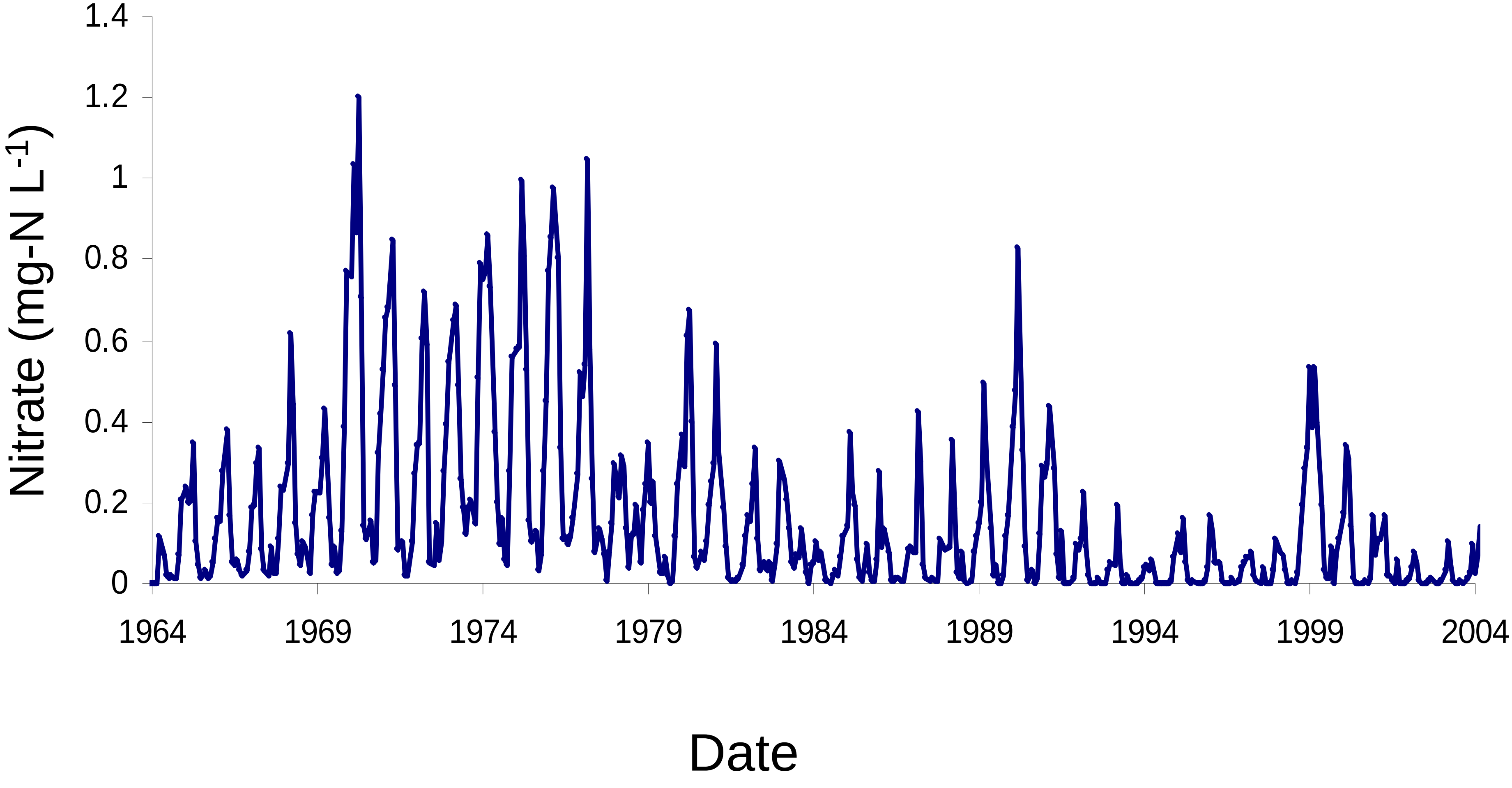
Figure 1

Monthly Stream Nitrate Concentrations (W6)



Modified from Likens 2004

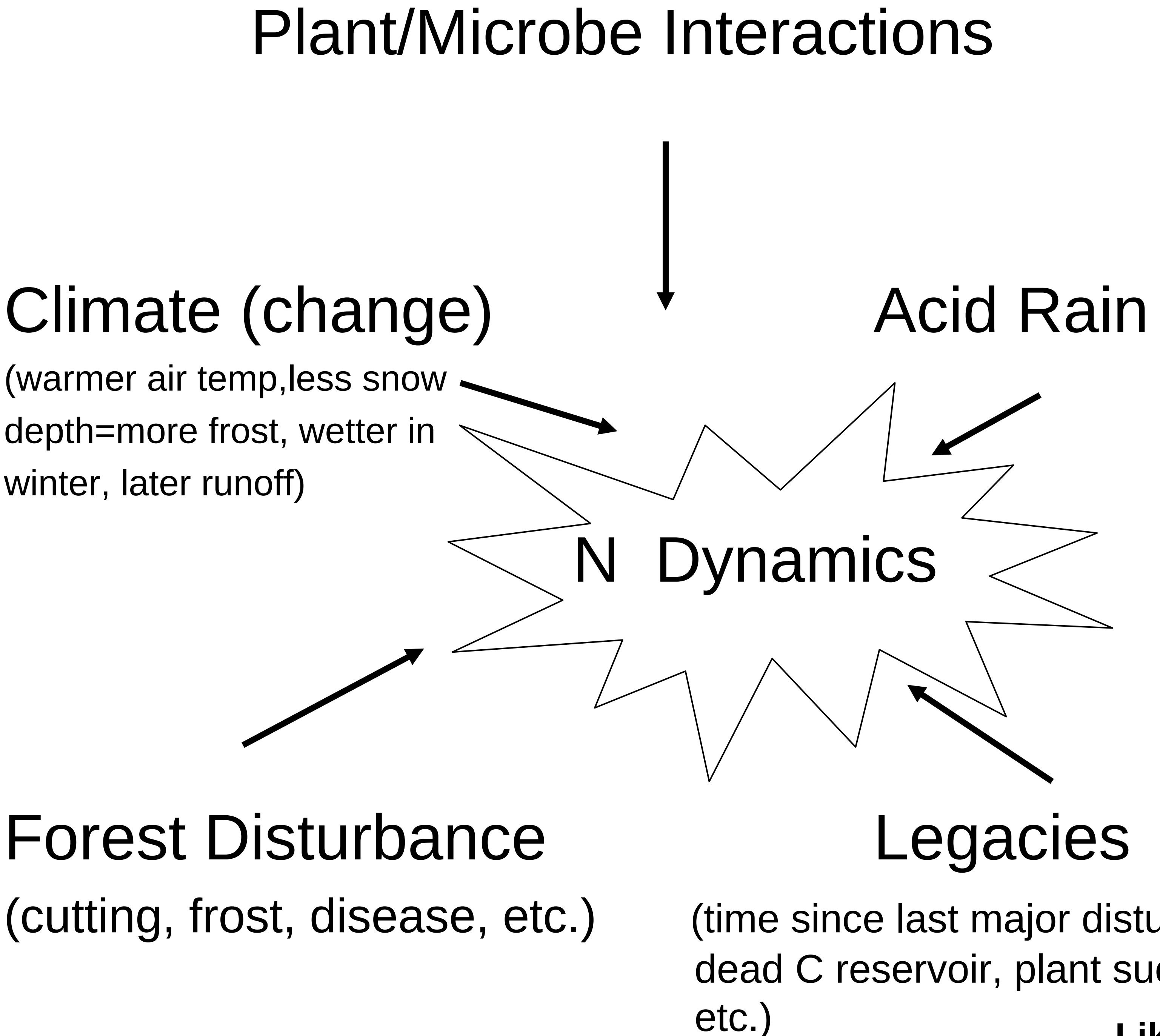


Figure 2

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Figure 3

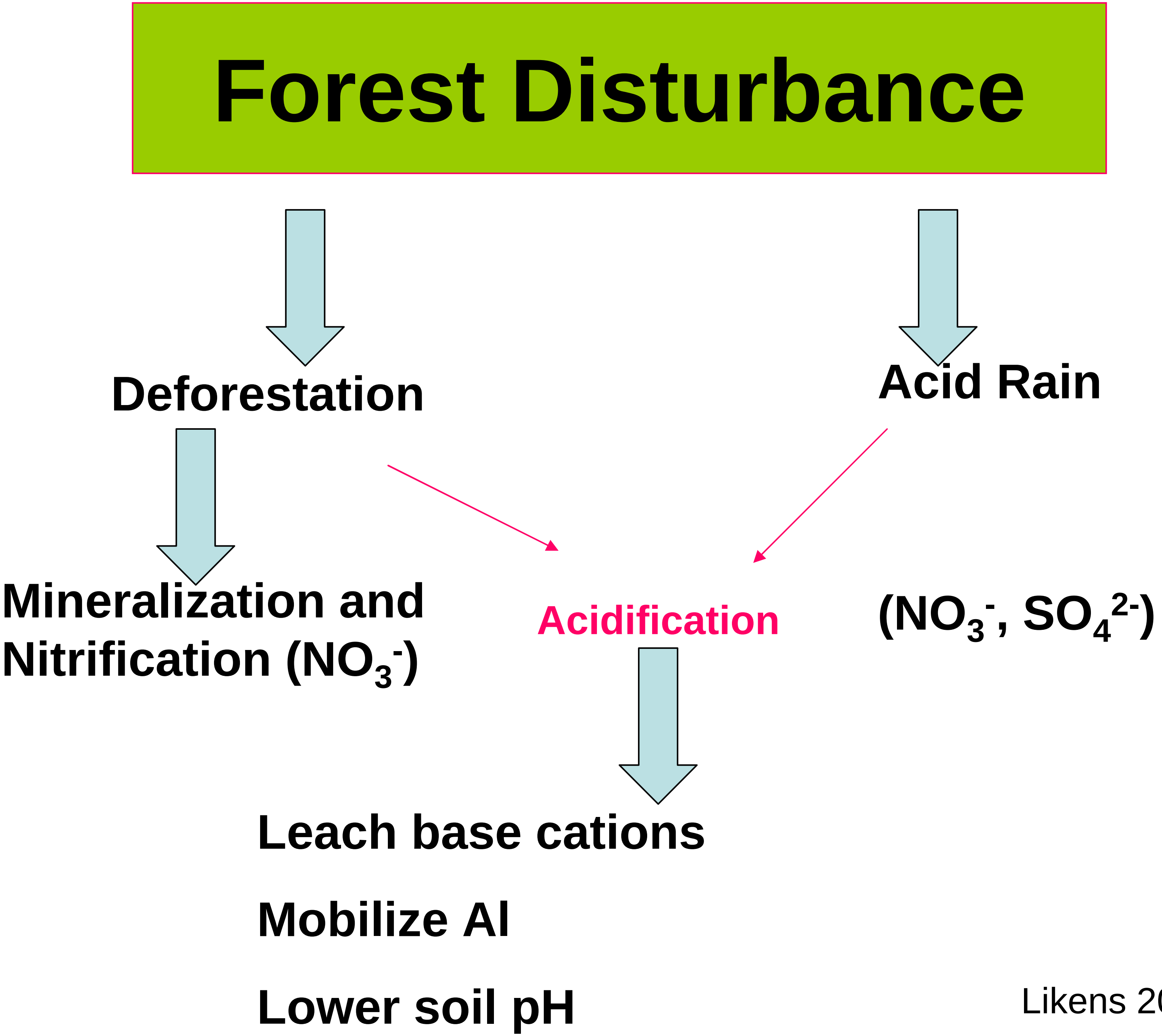

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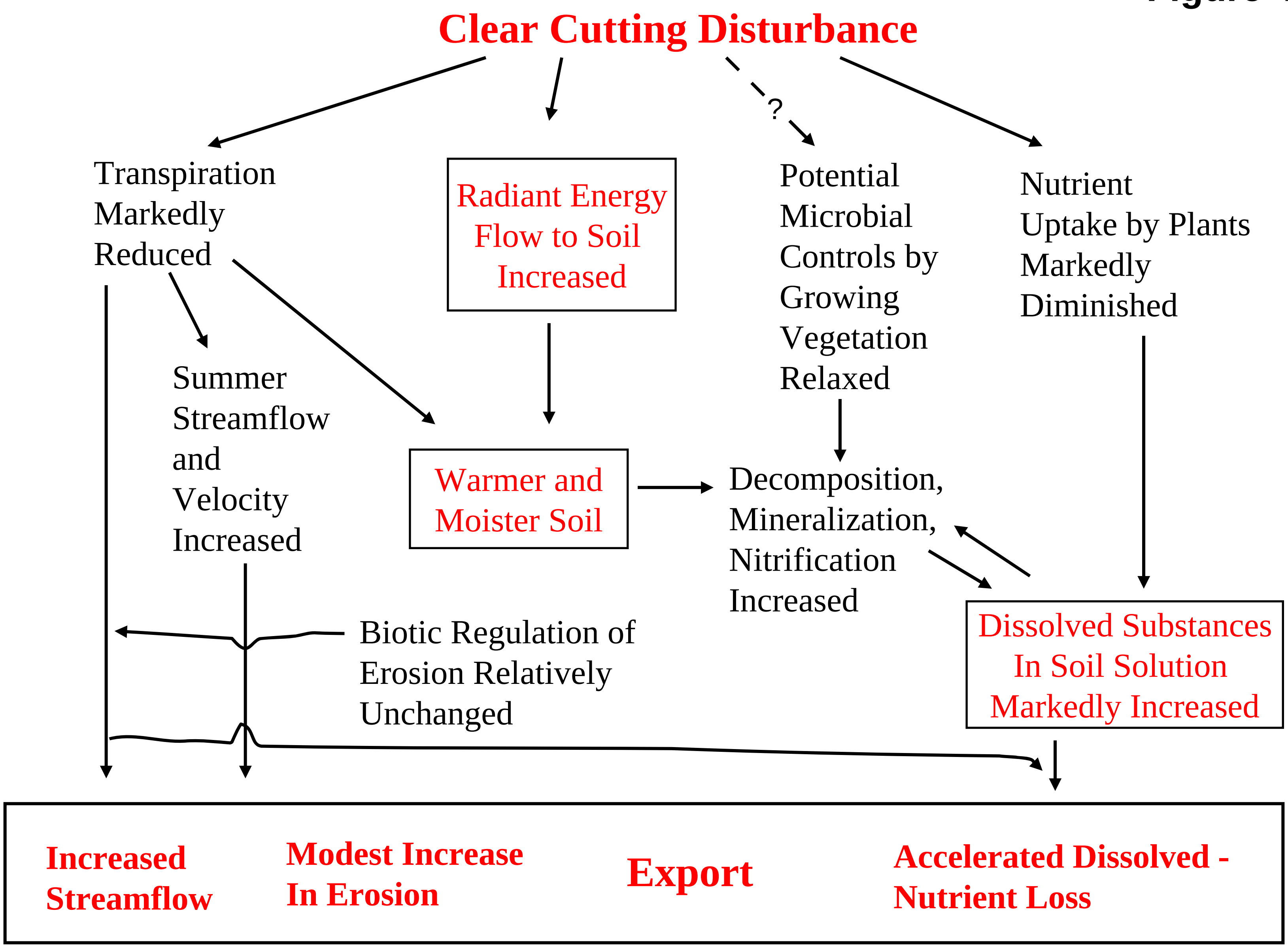
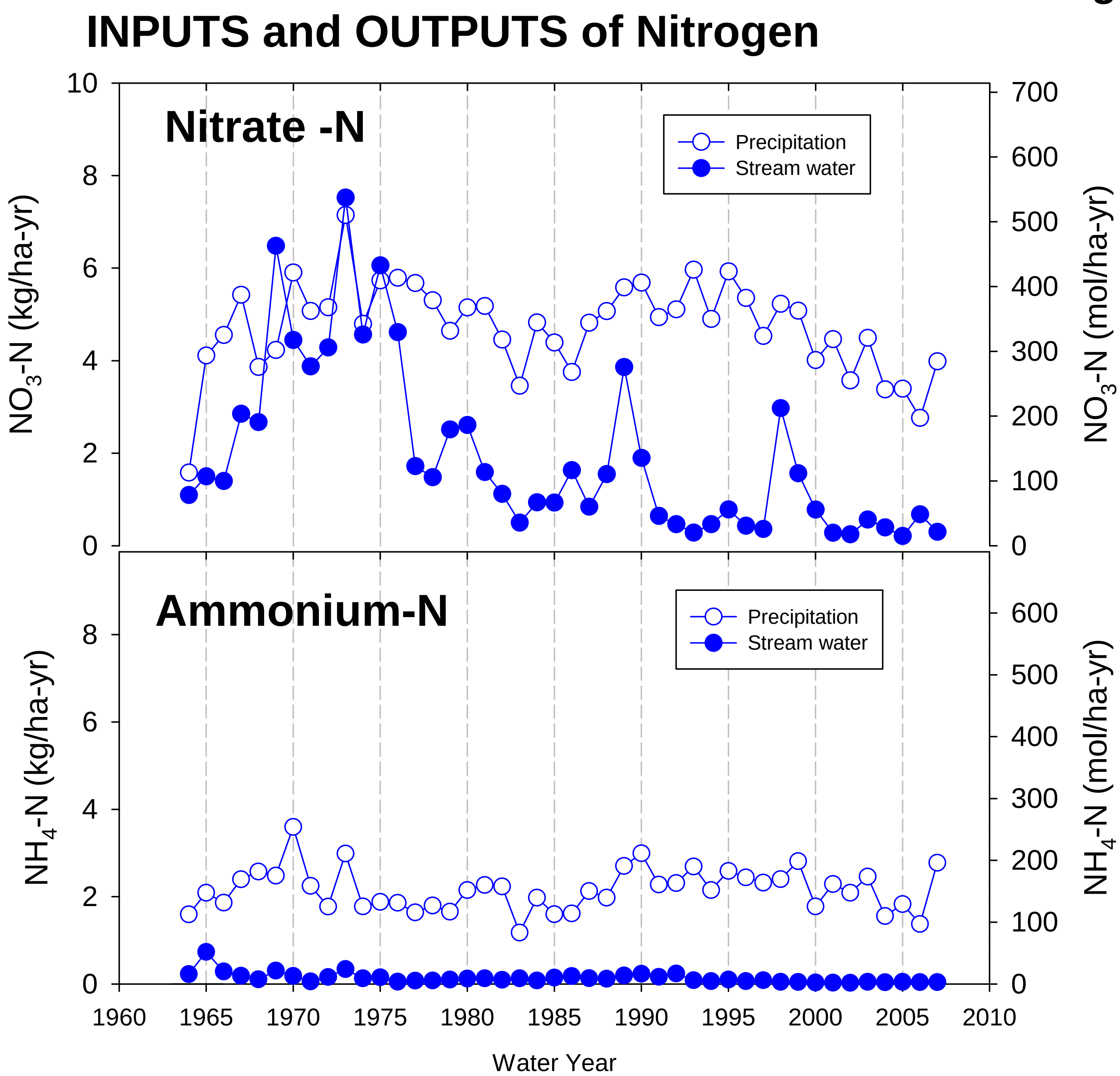
Figure 4



Bormann and Likens 1979

Figure 5



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The Global, Nitrogen Cycle in the Climate System: Models and Observations

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The global nitrogen cycle is one of the most altered biogeochemical cycles on earth. Bio-atmospheric exchanges of nitrogen have increased 3-5 fold since the pre-industrial era driven by increases in fossil fuel combustion and agricultural intensification. I will systematically examine the role of the nitrogen cycle in the climate system., including the observational constraints. Inclusion of a couple carbon and nitrogen cycle in the climate system predict an increase in atmospheric carbon dioxide in 2100 of more than 130 ppm. How realistic are these simulations? Are they able to reproduce the 1850 to current day increase in atmospheric carbon dioxide and nitrous oxide? Do the patterns of production produce realistic carbon to nitrogen ratios and carbon and nitrogen turnover rates in litter? Do the rates of nitrogen deposition used in the coupled simulations adequately capture the magnitude and distribution of nitrogen deposition? Have the rates of N deposition changed in the last 20-30 years? How well do we understand important the partitioning of wet and dry deposition for carbon uptake? What are the patterns of N_2O and NO emission and what is their likely role in the radiative forcing of climate? Understanding the role of the global N cycle in the Climate and Earth Systems requires a comprehensive effort that extends from the process to the global scale.

Nitrogen: a story of food, feed and fuel

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Introduction

Human activity converts more N_2 to nitrogen forms that can interact with the earth's biological, chemical and physical processes (termed 'reactive nitrogen', Nr) than do natural terrestrial processes (mostly biological nitrogen fixation (BNF) in unmanaged ecosystems). Most of the Nr is created as a consequence of food production and fossil fuel combustion. The Haber-Bosch process, invented in the early 20th century, now provides a virtually inexhaustible supply of nitrogen fertilizer. This one invention is responsible for the existence of about half of the world's population (Erisman et al., 2008). That's the good news. The other news is that most of this nitrogen (and additional amounts from fossil fuel combustion) is lost to the environment where it contributes to smog, greenhouse effect, ecosystem eutrophication, acid rain and loss of stratospheric ozone in a sequential manner—the Nitrogen Cascade.

This lecture will examine the impact of this increased N mobilization on the global N cycle by contrasting N distribution in the late-19th Century with those of the early-21st Century. It will review our understanding of the primary points of nitrogen loss to the environment, the impacts on people and ecosystems via the nitrogen cascade and the opportunities for an integrated nitrogen management plan at the local and national level. The lecture concludes with suggestions on how scientists can communicate the issues concerning nitrogen to both the public and to policy maker to ensure that society can optimize the use of nitrogen to provide food for the world's peoples, yet minimize the negative consequences on the environment.

Nr Creation

This section presents the sources and amounts of Nr produced by natural and anthropogenic processes in the past (1860) and the present (2005) (Galloway et al., 2004, 2008; Herridge et al., 2008). In 1860, the natural rate of Nr creation in unmanaged terrestrial ecosystems was on the order of 100 Tg N/yr. An additional ~ 5 Tg N/yr was fixed by lightning. Humans created Nr primarily by cultivation-induced BNF—on the order of 15 Tg N/yr.

Almost 1.5 centuries later, the world's population had increased over 4-fold with an even greater increase in food and energy production. These increases resulted in large increases in the Nr creation rate by humans. The Haber-Bosch process accounted for 120 Tg N/yr, fossil fuel combustion accounted for 25 Tg N/yr, and cultivation-induced BNF accounted for ~50 Tg N/yr, for a total of ~200 Tg N/yr. Conversely, natural terrestrial decreased by about 10% due to the loss of unmanaged lands.

Most of the Nr created by humans is lost to the environment. Fossil fuel combustion emits Nr directly into the atmosphere. For the Nr used in food production, about 80% is lost to the environment during the food production process, and the remaining 20% that is ingested by humans, is lost through excretion. A portion of the Nr lost to the environment is converted to N_2 via denitrification, however there is often a significant lag time between loss to the environment and N_2 formation. During this time, Nr accumulates and contributes to a number of environmental impacts.

Consequences of Anthropogenic Nr on Humans and Ecosystems

The atmosphere directly receives about 15% of the Nr created by human activities as a consequence of energy production; all of it is deposited as Nr. Agroecosystems receive 75%, most of which is either transferred directly into the atmosphere or hydrosphere or lost to the environment during the process of food production and consumption. The remaining 10% of the Nr is used in industrial processes. The primary beneficial effect of Nr introduced into agroecosystems is human nutrition; other effects occur as the Nr from agroecosystems cascades through other environmental systems (Galloway et al., 2003). In the atmosphere, increased Nr concentrations have direct and indirect impacts on human and ecosystem health on a regional and global basis.

Most of the Nr emitted to the atmosphere is deposited back to Earth's surface after hours to days. Increased Nr deposition to grasslands and forests has a residence time of years to centuries, introducing the potential for a large lag time in the cascade.

Because the production of N_2 is small relative to Nr inputs, N accumulates in a reactive form, resulting in initially increased productivity and some loss of biodiversity, and ultimately some loss of productivity. Several regions of the world have already reached the point where accumulation has slowed and loss of Nr to the atmosphere and hydrosphere has increased. Transfer of Nr from the atmosphere, agroecosystems, forests, and grasslands into the wetland–stream–river– estuary hydrosphere continuum is increasing and has resulted in numerous effects, including acidification, eutrophication, and human health problems. However, throughout the continuum there is a large potential for conversion of Nr to N_2, especially in wetlands, large rivers, estuaries, and the continental shelf. Thus, while the N cascade begins at the point of Nr creation, and while Nr will accumulate in and cycle among, most terrestrial systems, the cascade reaches an end at the continental margins, where its primary continuation is N_2O production during nitrification.

Management of Nr

Human intervention into the N cycle is needed again. Although this time, the intervention is needed to decrease the losses of Nr to environmental systems. Galloway et al. (2008) propose four specific interventions.

1. Decrease NOx formation during fossil fuel combustion: Using best available technologies, Nr creation during fossil fuel combustion can be decreased by about one third of its current level. The barriers to such a decrease are primarily financial, as the scientific, engineering and the policy instruments are all well developed.
2. Increase the nitrogen use efficiency (NUE) of crop production: It is estimated that there could be a 25% decrease in N fertilizer application to cereals if the current decline in cereal harvest area is halted and the crop yield response to applied N is increased by 20%.
3. Improve animal feeding strategies and manure management: It is estimated that 13% of the N lost from animal waste in the EU-27 countries could be either eliminated or captured by a combination of low-protein animal feeding, barn adaptations, covered manure storage, air purification and efficient manure applications.
4. Treat sewage better: Globally <1% of human sewage undergoes treatment that will convert it to N_2 (generally tertiary treatment or other forms of advanced wastewater treatment). As with NOx formation during fossil fuel production, the barriers to such a decrease are primarily financial, as the scientific, engineering and the policy instruments are all well developed.

Together, these four interventions represent a potential decrease of ~50 Tg N yr^{-1} created per year, or ~25% of the total Nr created in 2005 (Figure 1).

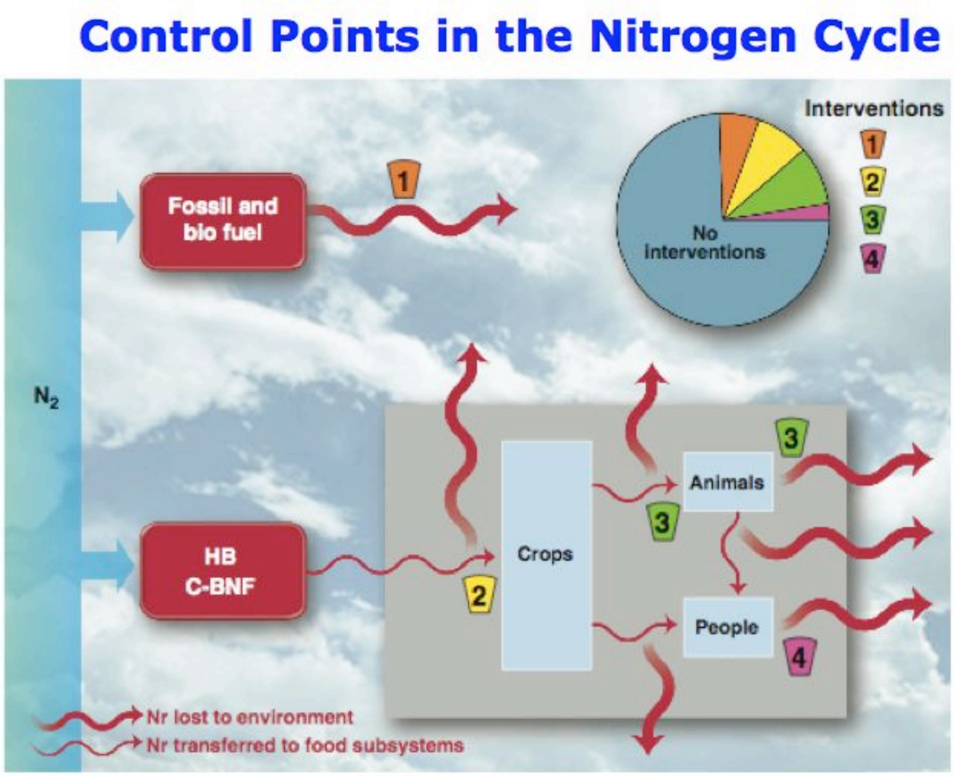


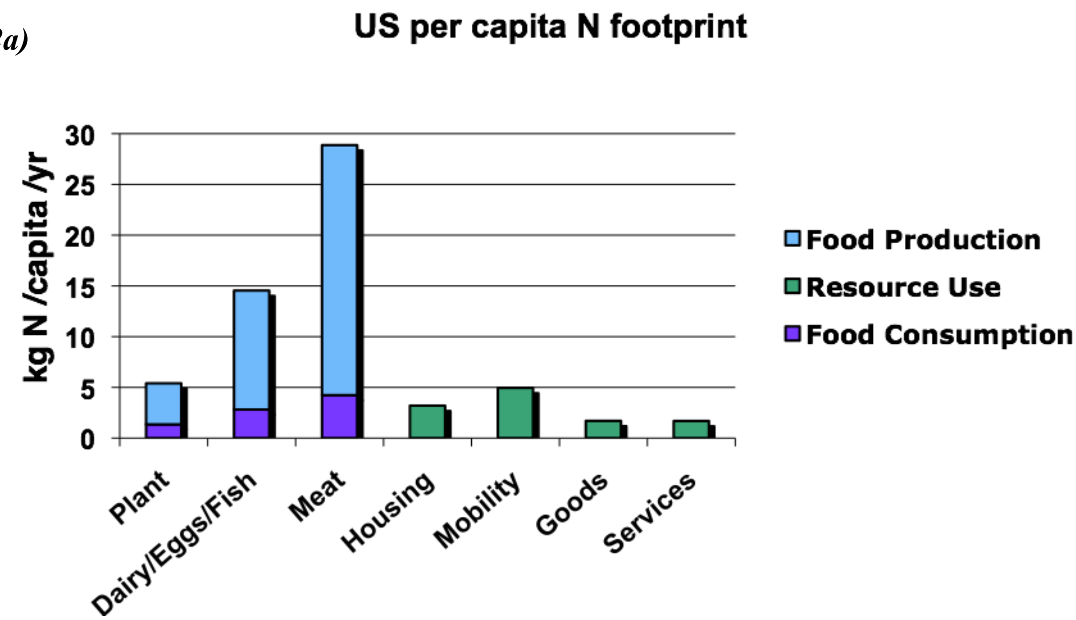
Figure 1: Conceptual model of where interventions in the N cycle can be used to decrease the amount of Nr created or the amount of Nr lost to the environment. The red boxes represent subsystems where Nr is created. The sky-background space represents the environment. Arrows leaving the red boxes either result in Nr lost to environment (fossil fuel and biofuel combustion) or inputs to the food production system (gray box). The light blue boxes within the gray box represent subsystems within the food production system where Nr is used. Nr can either enter these subsystems (thin red lines), or be lost to the environment (thick red lines). The numbers represent intervention points for N management. The pie chart shows the magnitude of Nr managed by the four interventions relative to the total amount created (187 Tg N) in 2005 (Galloway et al., 2008).

While these estimates are necessarily rough, and implementing them would not be trivial, they indicate that a multi-pronged, integrated approach can decrease the amount of Nr lost to the environment. Other intervention points are clearly needed if Nr creation rates are to decrease in the future. In addition, each intervention must be examined for unintended side effects. For example, conversion of Nr to N_2 via denitrification either directly (i.e., manure and sewage treatment facilities) or indirectly (use of wetlands to promote denitrification) could reduce surface water N loading. However this approach has an embedded problem—it could trade high concentrations of short-lived Nr species (e.g., nitrate) for higher concentrations of an Nr species (N_2O) that has an atmospheric lifetime of decades.

Broader Issues

Over the past decade, there have been significant advances in our scientific understanding of the magnitude, the consequences of human alteration of the nitrogen cycle, and how the nitrogen cycle can be managed without decreasing our ability to produce food. With these advances, a major challenge is to develop tools that can be used to communicate to the public why it is important to manage the N cycle, why they should be supportive, and what they can do. One such tool has recently been developed—the nitrogen footprint calculator. This tool, N-PRINT, provides information on how individual and collective action can result in less loss of nitrogen to the environment. N-Print, a project of the International Nitrogen Initiative, has been used to calculate the average per-capita nitrogen footprints of the US and The Netherlands. Initial results show that the average per-capita N footprint in the United States (Figure 2a) is greater than that of the Netherlands (Figure 2b), at 62 kg N/yr and 53 kg N/yr, respectively. For the US footprint, food production accounts for 50 kg N/yr, of which 42 kg N/yr is lost to the environment prior to food consumption, and 8 kg N/yr is lost to the environment after food consumption. For the Netherlands footprint, food production accounts for 43 kg N/yr, of which 36 kg N/yr is lost to the environment prior to food consumption, and 7 kg N/yr is lost to the environment after food consumption. Although the total amount of nitrogen consumed per capita in both countries is about the same, more meat is consumed in the US. Because more nitrogen is released to the environment throughout the food production process for meat, the total food production N footprint for the US is larger. The remaining portion of the N footprint in each country is lost to the environment from the mobility, goods, and services sectors.

2a)



2b)

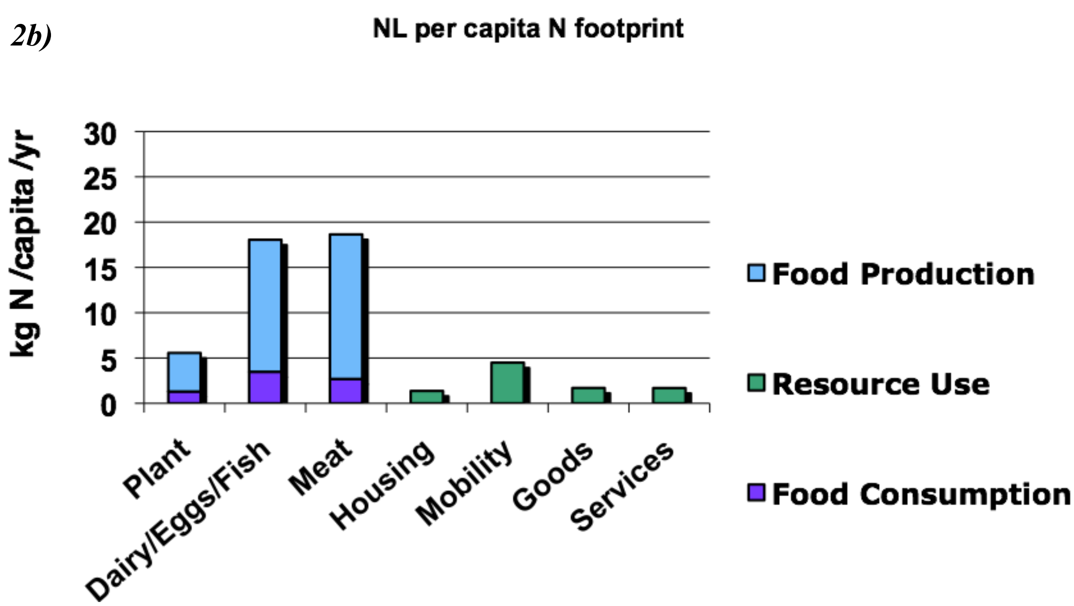


Figure 2: The average per-capita Nitrogen Footprint for the US (a) and the Netherlands (b). The green bars (resource use) are primarily associated with fossil fuel derived NOx emissions from the housing, mobility, goods and services sectors. The blue bars represent the N that is consumed by the average person in the plant, dairy/eggs/fish and meat food groups. The red bars represent the N lost to the environment before consumption due to the production of those food groups.

These results were presented at the Workshop on *N Deposition, Critical Loads and Biodiversity* held November 16-18, 2009 in Edinburgh Scotland (Leach et al., 2009).

Conclusions

Human activity has profoundly altered the nitrogen cycle to the detriment of both human and ecosystem health. The magnitude of the impacts is increasing with time as a growing burden of reactive nitrogen is accumulating in environmental reservoirs. However, just as the current state of the nitrogen cycle is due to human action, so can the movement of the nitrogen cycle closer to its natural state be caused by human actions. To accomplish this will require the close cooperation between the scientific, engineering and decision-making communities, along with a strong public outreach program to ensure ultimate success.

Acknowledgments
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Scale transitions and paradoxes in the tropical land nitrogen cycle

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Despite the well-recognized importance of tropical land ecosystems in the Earth's carbon-climate system, there remain fundamental uncertainties in our understanding of the nutrient cycles that govern these systems worldwide. One of the most vexing problems lies in the resolution of the nitrogen cycle across this vast and variable biome, and a series of mismatches between local vs. larger-scale representations of governing mechanisms. I will here examine our understanding of biogeochemical cycles in tropical land ecosystems, with emphasis on the urgent need to understand how mechanisms that operate at the level of physiology of individual organisms translate to dynamics at the aggregate scale of ecosystems and biomes. I will focus on the role of nitrogen fixation as an individual-based process capable of generating great excess in nitrogen relative to other nutrients within tropical biomes. In conclusion, I will discuss how individual-based processes can become dynamically important at the scale of the entire coupled Earth carbon-climate system.