Box 3.6. The Global Nitrogen Cycle: Past, Present and Future[1]

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In the late-twentieth century human activities surpassed natural terrestrial processes in converting unreactive N_2 to reactive N (Nr)[2]. This fact has great significance because not only is N the very stuff of life, but the lack of Nr is often limiting to the productivity of ecosystems and too much Nr contributes to most environmental issues of the day.

Nr creation requires the breaking of the triple bonds within the N_2 molecule, a reaction that requires energy. In nature N_2 is converted to Nr mainly by biological nitrogen fixation (BNF), performed 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 (Vitousek et al. 2002). 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. In addition, N_2 can also be converted to Nr during lightning strikes. In the pre-human world BNF was the dominant means by which new Nr was made available to living organisms. Humans create Nr in three ways: cultivation-induced BNF (e.g., legume production), Haber-Bosch process (industrial fixation of N_2 to NH_3), and fossil fuel combustion (high temperature conversion of N_2 and fossil organic N to NO_x). By about 1970 anthropogenic processes overtook natural terrestrial process in Nr creation on a global scale.

The impact of this significant increase in the rate of Nr creation on the global N cycle is illustrated by contrasting Nr creation and distribution from 1890 to 1990. The former is an appropriate starting point for examination of the N cycle since at that time limited Nr was created by human activities. Although the global population was ~25% of the current number, the world was primarily agrarian and produced only 2% of the energy and 10% of the grain produced today. Most energy (75%) was provided by biomass fuels; coal provided most of the rest (Smil 1994). Petroleum and natural gas production was limited and was of little consequence relative to the global supply of energy and the creation of Nr as NO_x through combustion. In total, fossil fuel combustion created only about 0.6 Tg N yr^{-1} in 1890, through production of NO_x (Fig. 3.54).

Crop production was primarily sustained by recycling crop residue and manure on the same land where food was raised. Since the Haber-Bosch process was not yet invented, the only new Nr created by human activities was by legume and rice cultivation (the latter promotes Nr creation because rice cultivation creates an anaerobic environment which enhances nitrogen fixation). While estimates are not available for 1890, Smil (1999) estimates that in 1900 cultivation-induced Nr creation was on the order of 15 Tg N yr^{-1}. Additional Nr was mined from guano (~0.02 Tg N yr^{-1}) and nitrate deposits (~0.13 Tg N yr^{-1}) (Smil 2000).

Thus in 1890 the total anthropogenic Nr creation rate was ~15 Tg N yr^{-1}, almost entirely for food production. In contrast, the natural rate of Nr creation was on the order of 220 Tg N yr^{-1}. Terrestrial ecosystems created ~100 Tg N yr^{-1} and marine ecosystems created ~120 Tg N yr^{-1} (D. Capone, personal communication). An additional ~5 Tg N yr^{-1} was fixed by lightning. On a relative basis for the globe, human activities created about 5% of the total Nr fixed and about 13% when only terrestrial systems are considered.

One century later the world's population had increased by a factor of ~3.5, from about 1.5 to about 5.3 billion, but the global food and energy production increased about 7-fold and 90-fold, respectively. Just as was the case in 1890, in 1990 (and now) food production accounts for most of the new Nr created. What changed most since 1890 was the magnitude of Nr created by humans. Smil (1999) estimated that in the mid-1990s cultivation-induced Nr production was ~33 Tg N yr^{-1}. The Haber-Bosch process, which did not exist in 1890, created an additional ~85 Tg N yr^{-1} in 1990, mostly for fertilizer (~78 Tg N yr^{-1}) and the remainder in support of industrial activities such as the manufacture of synthetic fibers, refrigerants, explosives, rocket fuels, nitroparaffins, etc.

For energy production, during the period 1890 to 1990, much of the world was transformed from a bio-fuel to a fossil-fuel economy. The increase in energy production by fossil fuels resulted in increased NO_x emissions from ~0.6 Tg N yr^{-1} in 1890 to ~21 Tg N yr^{-1} in 1990. By 1990 over 90% of energy production resulted in the creation of new Nr, in contrast to 1890 where very little energy production caused Nr creation.

By 1990 Nr created by anthropogenic activities was ~140 Tg N yr^{-1}, a ~9-fold increase over 1890, contrasted to a ~3.5-fold increase in global population. Coupled with the increase in Nr creation by human activities was a decrease in natural terrestrial N fixation because of conversion of natural grasslands and forests to croplands, etc., from ~100 Tg N yr^{-1} to ~89 Tg N yr^{-1} (Cory Cleveland, pers. comm.).

The fate of anthropogenic Nr for the three anthropogenic sources is clear: NO_x from fossil fuel combustion is emitted directly into the atmosphere; RNH_2 from rice and legume cultivation is incorporated into biomass; NH_3 from the Haber-Bosch process is primarily converted into commercial fertiliser, which is applied to agroecosystems to produce food. However, little of the fertiliser N actually enters the human mouth in the form of food; most is in fact ultimately released to environmental systems.

In 1890 both the creation and fate of Nr was dominated by natural processes (Fig. 3.54a). There were limited Nr transfers via atmospheric and hydrologic pathways relative to the amount of Nr created. For terrestrial systems, of the ~115 Tg Nr yr^{-1} created, only about ~15 Tg N yr^{-1} were emitted to the atmosphere as either NH_3 or NO_x. There was limited connection between terrestrial and marine ecosystems; only about 5 Tg N yr^{-1} of dissolved inorganic nitrogen was transferred via rivers into coastal ecosystems in 1890 and only about 17 Tg N yr^{-1} were deposited to the ocean surface.

In 1990 by contrast, when creation of Nr was dominated by human activities (Fig. 3.54b), there were also significant changes in Nr distribution. NH_3 emissions increased from ~9 Tg N yr^{-1} to ~43 Tg N yr^{-1} as a consequence of food production; NO_x emissions increased from ~7 Tg N yr^{-1} to ~34 Tg N yr^{-1} from both energy and food production. The increased emissions resulted in widespread distribution of Nr to downwind ecosystems. Transfer of Nr to marine systems also increased. By 1990 riverine fluxes of dissolved inorganic nitrogen to the coastal ocean had increased to 20 Tg N yr^{-1} and atmospheric N deposition to marine regions had increased to 27 Tg N yr^{-1}. While evidence suggests that most of the riverine N is denitrified in coastal and shelf environments (Seitzinger and Giblin 1996), most of the atmospheric flux is deposited directly to the open ocean, although a portion of the 27 Tg N yr^{-1} is deposited to coastal ocean and shelf regions, with significant ecological consequences (Rabalais 2002).

A key component missing from Fig. 3.54b is the ultimate fate of the ~140 Tg N yr^{-1} Nr created by human action in 1990. On a global basis, Nr created by human action is either accumulated (stored) or is denitrified. Unfortunately, it is not possible to estimate the relative importance of these two processes. This in-

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1 Adapted primarily from Galloway and Cowling (2002).

2 The term reactive nitrogen (Nr) as used in this box includes all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere of the Earth. Thus Nr includes inorganic reduced forms of N (e.g., NH_3, NH_4^+), inorganic oxidised forms (e.g., NO_x, HNO_3, N_2O, NO_3^-), and organic compounds (e.g., urea, amines, proteins).

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ability represents one of the largest uncertainties in the understanding of the nitrogen budget at any scale.

There are thus large uncertainties regarding the rates of Nr accumulation in various reservoirs. This limits the ability to determine the temporal and spatial distribution of environmental effects. These uncertainties are even more significant because of the sequential nature of the effects of Nr on environmental processes. This sequence of transfers, transformations and environmental effects is referred to as the nitrogen cascade (Galloway et al. 2003). A single atom of newly created Nr (as either NH_x or NO_x) can alter a wide array of biogeochemical processes and exchanges among environmental reservoirs. For example, a molecule of NO emitted to the atmosphere during fossil fuel combustion can, in sequence, increase ozone concentrations in the troposphere, decrease atmospheric visibility and increase concentrations of PM2.5 particles, increase precipitation acidity, increase soil acidity, increase or decrease forest productivity, increase surface water acidity, increase hypoxia in coastal waters, increase greenhouse warming, and decrease stratospheric ozone.

A principle feature of the cascade is the accumulation rate of Nr in environmental systems. This is one of the most important research questions associated with the impact of humans on the nitrogen cycle. Human creation of Nr will continue to increase in the future as population grows. Even after population has peaked Nr creation is still likely continue to increase due to growth in per capita resource use. How high will the Nr creation rate go? In 1990 it was ~140 Tg N yr^{-1}, and the average per capita Nr creation rate was ~24 kg N $person^{-1}$ yr^{-1}, ranging from ~7 kg N $person^{-1}$ yr^{-1} in Africa to ~100 kg N $person^{-1}$ yr^{-1} in North America. If the global population peaks at ~8.9 billion people and if all people had the same per capita Nr creation rate from food and energy production as North America in 1990 (~100 kg N $person^{-1}$ yr^{-1}), then the total Nr creation rate would be ~900 Tg N yr^{-1}, with about half occurring in Asia. Given the environmental concerns about Nr, it is unlikely that this value will be reached. What the final maximum Nr creation rate turns out to be, however, will depend to a very large extent on how the world manages its use of nitrogen for food production and its control of N in energy production in future.

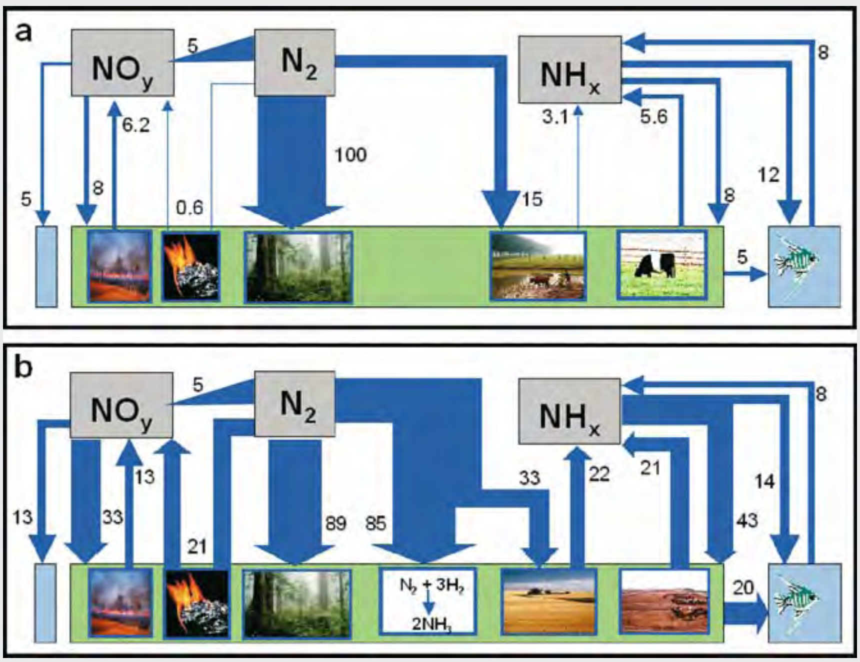

Fig. 3.54. Global terrestrial nitrogen budget for **a** 1890 and **b** 1990 in Tg N yr^{-1}. The emissions to the *NO_y box* from the *coal* reflect fossil fuel combustion. Those from the *vegetation* include agricultural and natural soil emissions and combustion of biofuel, biomass (savanna and forests) and agricultural waste. The emissions to the *NH_x box* from the *agricultural field* include emissions from agricultural land and combustion of biofuel, biomass (savanna and forests) and agricultural waste. The NH_x emissions from the *cow* and *feedlot* reflect emissions from animal waste. The transfers to the *fish box* represent the lateral flow of dissolved inorganic nitrogen from terrestrial systems to the coastal seas

3.4 Putting Human-Driven Changes into an Earth System Perspective

Most of this chapter has considered the ways in which human activities are changing the Earth System by examining a large number of detailed pieces – the human driving forces and the resulting changes in the Earth System. It should be clear from the foregoing discussion that many of the system changes occur due to interactions among a large number of human activities, aggregated globally over long periods of time. Several properties of these interactions emerge as important features of an altered Earth System.

3.4.1 Socioeconomic and Cultural Teleconnections

Just as connections in the biophysical part of the Earth System link processes across long distances (see Sect. 2.5), socioeconomic and cultural connections link human activities in widely separated regions of the planet. Two of the most important of these are urbanisation and globalisation. Together they are linking and moving people, processes and products across the Earth. Any understanding of the evolving human role in the functioning of the Earth System must take into account this accelerating human planetary network that is transforming the anthroposphere.

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