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NITROGEN

Regional Contributions to the Global Cycle

By G. Philip Robertson

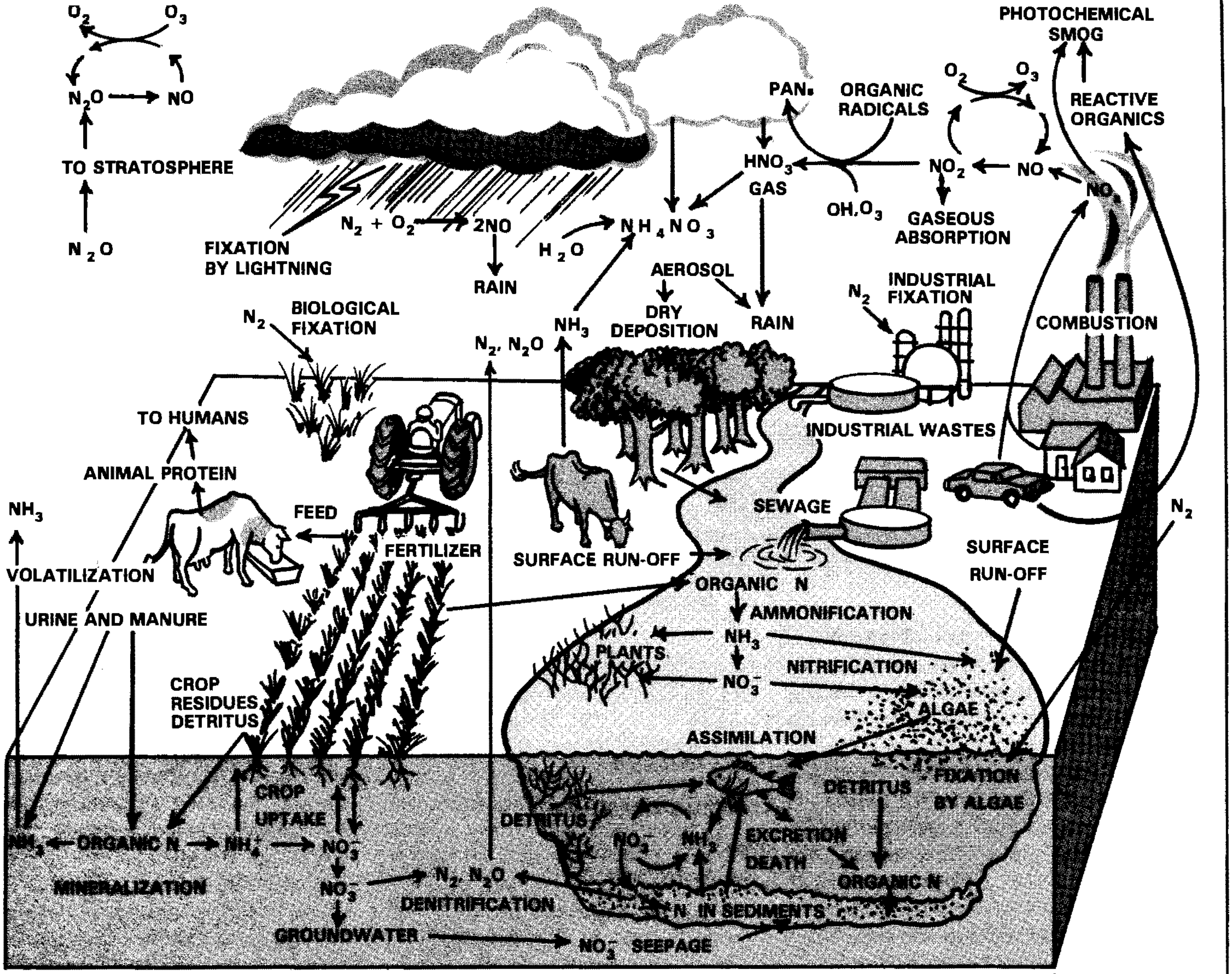
Nitrogen is critical for life on Earth: it is an integral component of all amino acids, the basic constituents of protein. Although elemental nitrogen is abundant—the Earth's atmosphere is 79 percent nitrogen—the availability of nitrogen often limits the productivity of plant communities, whether natural vegetation or agricultural crops. This is because only certain forms of nitrogen are available to most organisms, and these forms are generally in short supply. Much effort has been devoted to understanding these forms of nitrogen—in particular, their abundance and the rates at which they are transformed from one form to another.

We now have an excellent qualitative understanding of most parts of the overall nitrogen cycle, including the ways in which anthropic (human-induced) influences can affect major portions of it. (See also Robert B. Cook, "Man and the Biogeochemical Cycles: Interacting with the Elements," *Environment*, September 1984.) Such influences can have important consequences at many geographic scales: at the local level, anthropic changes in the cycle can affect crop productivity and perhaps surface-water eutrophication; at the regional level, nitrogen cycle changes can affect groundwater quality, acid precipitation fluxes, and the eutrophication of coastal wetlands; and at the global scale, changes in nitrogen cycling may affect global temperatures, the incidence of ultraviolet light reaching the Earth's surface, and patterns of primary productivity in the world's oceans.

Our understanding of the importance of nitrogen cycle changes for the global environment is especially lacking. Two sets of fluxes in particular are important: emissions of nitrous oxide (N_2O) and other nitrogen oxides (NO, NO_2) to the atmosphere and nitrate (NO_3^-) leaching to groundwater. Both sets of fluxes are biologically mediated, accelerated by human activity, and of global concern.

Nitrous oxide, for example, is one of the important greenhouse gases in the atmosphere, and in the lower stratosphere photolytically decomposes to nitric oxide (NO), which reacts with free hydroxyl radicals to catalyze ozone degradation.[1] Changes in global nitrous oxide fluxes may thus affect both large-scale temperature trends and, together with changes in other nitrogen oxide fluxes, may affect the Earth's ultraviolet radiation balance. In the case of nitrate leaching, nitrate pollution of groundwater aquifers is a growing public health concern in both developed and Third World countries,[2] and nitrate seepage into rivers, in combination with nitrogen from surface run-off, may lead to the eutrophication of coastal wetlands and marine systems,[3] with subsequent effects on open oceans.

To a large degree, we lack an understanding of the environmental consequences of the important nitrogen fluxes that can be affected by human activity because we lack a solid quantitative understanding of major fluxes at the global scale. Understanding global fluxes requires knowledge not only about the behavior of nitrogen species in the environment, but also about the size of anthropic changes in these fluxes relative to changes in natural background rates. It is this quantitative



The nitrogen cycle and anthropic activities that affect nitrogen fluxes.

SOURCE: Adapted from National Research Council, *Nitrates: An Environmental Assessment* (Washington, D.C.: National Academy Press, 1978).

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estimate of overall significance that has proved difficult to evaluate, and that has stimulated the development of regional nitrogen models.

Global Nitrogen Models

Largely in response to the need to evaluate the importance of human alterations on the global nitrogen cycle, several studies in the mid-1970s attempted to piece together models of global nitrogen cycling.[4] What emerged (see Table 1 on page 18) was remarkably precise consensus for some fluxes such as biological nitrogen fixation in terrestrial environments, an equally remarkable lack of consensus for other fluxes such as nitrogen fixation in marine systems, and similar but very imprecise estimates for still other fluxes such as terrestrial nitrogen gas emissions. Uncertainties for some of these fluxes spanned orders of magnitude.

Since these studies, there have been no other published attempts to revise the global nitrogen cycle. This may reflect a certain frustration regarding global models. If the levels of uncertainty for many important fluxes cannot be reduced to reasonable levels, then such models may be of little use for guiding research and policy decisions.

Yet existing models, as crude as they are, are important tools for understanding the complexity of global nitrogen flows.[5] At a basic level, they are useful as conceptual frameworks within which to organize current perceptions of how the global cycle operates. Even crude balances enable one to evaluate data needs by highlighting information gaps and thereby encourage the design of more comprehensive monitoring programs. And as parts of global budgets become more precise, the models can put nitrogen pools and fluxes into perspective, lending considerable insight into interactions among processes or reservoirs that may appear unrelated. Eventually, sensitivity analysis will allow us to predict the importance of anthropic changes in the nitrogen cycle to the overall health of the global environment. In the meantime we must concentrate on adding precision to the existing models.

TABLE 1
ESTIMATES OF THE MAJOR FLUXES IN THE GLOBAL NITROGEN CYCLE

NITROGEN FLUX	SÖDERLUND AND SVENSSON	CAST	DELWICHE	NRC
		(10^9 kilograms per year)		
TERRESTRIAL SYSTEMS				
Inputs				
N_2 fixation				
biological	139	149	99	139
industrial	36	57	40	70
combustion (NO_x)	19	20	18	21
NH_4^+/NH_3 deposition				
wet	30–60	—	65	
dry	61–126	—		
NO_3^-/NO_x deposition[a]				66–200
wet	13–30	30	25	
dry	19–53	—		
Outputs				
Denitrification (N_2 only)	91–92	67–93	120	197–390
N_2O emission[b]	16–69	4–7		
NO_x emission				
soil	21–89	—	—	11–33
fire	—[c]	—	—	10–200
industrial combustion	19	21	18	21
NH_3 emission				
biological	22–41	—	53	11–33
coal	4–12	—		
unidentified	87–191	—	22	
River discharge	18–33	—	35	18
AQUATIC AND MARINE SYSTEMS				
Inputs				
Biological N_2 fixation	30–130	—	30	110
River discharge	13–24	—	35	18
NH_4^+/NH_3 deposition				
wet	8–25	—	14	
dry	11–25	—		
NO_3^-/NO_x deposition				17–42
wet	5–16	—	0.9	
dry	6–17	—		
Outputs				
Denitrification (N_2 only)	25–179	1–100	40	0–120
N_2O emission				
NO_x emission	0	—	—	11–33
NH_3 emission	—	—	—	18–45
Sedimentation	38	—	—	30–40

[a] Includes lightning-produced NO_x
[b] Includes N_2O from denitrification
[c] May be included in soil flux

SOURCES: R. Söderlund and B. H. Svensson, "The Global Nitrogen Cycle," *Ecological Bulletins—NFR* 22(1976):23–73; Council for Agricultural Science and Technology (CAST), "Effect of Increased Nitrogen Fixation on Stratospheric Ozone," *CAST* 53(1976):1–33; C. C. Delwiche, "Energy Relations in the Global Nitrogen Cycle," *Ambio* 6(1977):106–11; National Research Council, *Nitrates: An Environmental Assessment* (Washington, D.C.: National Academy Press, 1978).

Regional Models

Most estimates of natural global nitrogen fluxes are based on extrapolation from more-intensive studies at the small-watershed or soil-type level. For most fluxes few intensive studies exist relative to the large number of different watershed and soil types of the Earth, and therefore, extrapolations tend to magnify uncertainty. Most existing models assume, for example, that all forests of the world fix nitrogen at a mean rate of 10 kilograms per hectare per year, based mainly on rates in eastern U.S. deciduous forests.[6] This estimate assumes that variations that are due to climate (tropical versus temperate, for example) and stand age (early successional versus old growth vegetation) are unimportant, although we know that at a local level either of these two variables can affect most nitrogen fluxes by at least an order of magnitude. The conceptual leap from primary watershed to global environment may not be large, but the numerical leap is enormous.

The National Academy of Sciences panel that constructed the most recent global nitrogen budget[7] suggested regional-scale mass-balance models as a logical solution to imprecision problems. Dividing the globe into discrete regions, they argued, be they biogeographical or sociopolitical, should allow one to define model compartments of, for example, soil and groundwater at a resolution appropriate to the region. Combining similar compartments from different regions will then

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Nitrogen is lost to the atmosphere through combustion. Globally, the burning of forests for land clearing may be an overlooked but significant source of the nitrous oxide responsible for stratospheric ozone depletion. (Photo: R. Aguirre and G. Switkes, AMAZONIA/BPS)

allow straightforward extrapolation to the globe.

As an illustration of the value of this approach, consider a recent estimate of nitrogen fixation in the Amazon River Basin[8] based on fluxes in three different forest-soil types (see Table 2 on page 20). This approach yields an estimate of 12×10^9 kilograms per year for nitrogen fixation from the basin as a whole, whereas a mean flux based on rates in eastern U.S. forests (10 kilograms per hectare per year) extrapolates to only 6×10^9 kilograms of nitrogen per year.

Regional-level studies such as this simple Amazon model offer the additional advantage of providing insight into regional-scale questions. For example, the impact of cattle feedlot operations on groundwater quality is difficult to evaluate from models that aggregate groundwater questions into continent-level river discharge compartments. Regional models with groundwater compartments can address this question directly.

Existing Regional Budgets

Comprehensive regional models exist today for the states of Wisconsin and Florida, for two river valley basins in California, for the United Kingdom, and for West Africa south of the Sahara.[9] Less-complete models—focusing on only a few major compartments—have been constructed for the continental United States, for the Amazon Basin, for the open ocean, and for the Baltic Sea.[10] We are a long way from having a sufficient number of regional budgets to combine into a new global synthesis, but many of the models nevertheless offer significant insight into global-level problems.

The regional models for the two states and West Africa are of particular interest to those concerned about the impacts of industrial fertilizer use and tropical deforestation on global nitrogen cycles. The nitrogen balance for Wisconsin,[11] for example, was constructed mainly in response to concerns that the nitrogen fertilizer being applied to Wisconsin farmland in increasingly higher quantities (see Figure 1 on page 20) is not being utilized by the crops as efficiently as it might be. This fertilizer may thus be contributing to groundwater contamination, to surface-water eutrophication, and to stratospheric ozone depletion via nitrous oxide production. The aim of the West Africa model,[12] on the other hand, was in part to provide a Third World contrast against which models for industrialized regions could be compared in order to evaluate some of the effects of industrialization. The model was also designed to provide a means for evaluating the effects of tropical deforestation on nitrous oxide production and on nitrogen loading of coastal areas, and to provide insight into ways that existing nitrogen resources in low-input tropical cropping systems could be conserved.

The relative magnitudes of both nitrogen inputs and losses within these regions are striking (see Table 3 on page 29). In West Africa, for example, biological nitrogen fixation and atmospheric deposition accounted for 99 percent of all nitrogen inputs to the region in the base year, 1978. In Wisconsin in 1974 these fluxes contributed only 68 percent of the total input, with fertilizer and commodity imports (mainly food) making up the difference.

Differences in nitrogen losses are even more pronounced. Nitrogen oxides emitted from burning vegetation accounted for 73 percent of the total nitrogen lost from West Africa; in Wisconsin this flux was neligible. Most of the remaining loss in West Africa (24 percent) was from the combined effects of denitrification, leaching, erosion, and nitrogen oxide emissions from soil. In contrast, Wisconsin agriculture in 1974 lost over 60 percent of its nitrogen to denitrification, leaching, erosion, and soil nitrogen oxide emissions; another 24 percent to ammonia volatilization; and the remaining 15 percent to commodity exports.

Because the nitrogen fluxes in Wisconsin do not include those from nonagricultural areas, the relative importance of anthropic fluxes such as fertilizer inputs is somewhat overstated in this analysis; nevertheless, this omission should not much affect overall trends, as Wisconsin land use and economic activity are much more heavily skewed toward intensive agriculture than are these activities in West Africa. The inclusion of nonagricultural areas in the Wisconsin model, for example, changes the percentage of all fixed nitrogen provided by fertilizer only 4 percentage points, from 26 percent to 22 percent.[13]

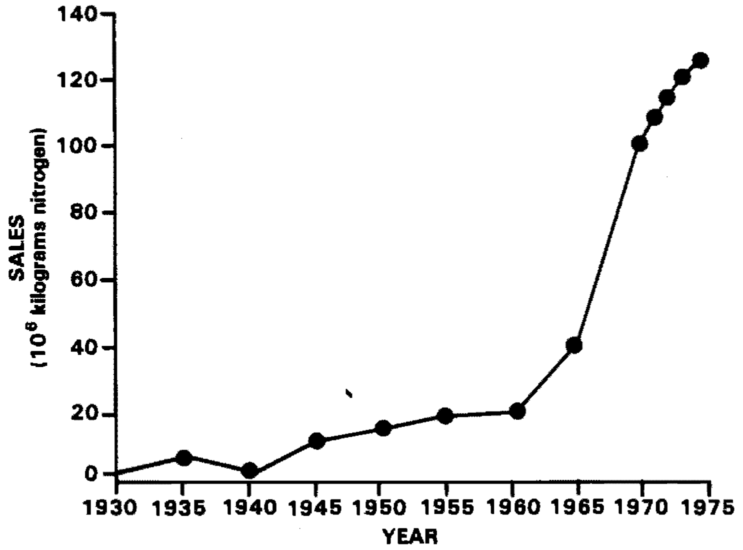
The differences in major nitrogen fluxes from these two regions suggest different impacts on the global nitrogen balance and different ways to optimize nitrogen use within the regions' cropping systems. Of the 582 $\times$ 10^6 kilograms of nitrogen entering Wisconsin agriculture in 1974, almost 60 percent was lost to hydrologic and gaseous fluxes. Although there can be little doubt that the absolute quantities in 1974 far exceeded losses during the prefertilizer era, precise evaluation of the impact of this loss on water quality and concentrations of atmospheric trace gases is difficult because it requires differentiating between gaseous and hydrologic fluxes. The model does show, however, that because most of the nitrogen lost is from the available nitrogen in the soil compartment, direct additions to this pool from fertilizer use will result in far greater nitrogen losses than would result from nitrogen additions to other pools such as the nitrogen held in soil organic matter. The model, in fact, suggests that a doubling of fertilizer use would more than double the losses of nitrogen from the system. Clearly, better management of nitrogen resources—both biological and fertilizer—would help to reduce losses and bring nitrogen inputs in Wisconsin more in balance with losses.

TABLE 2
NITROGEN FIXATION IN UNCUT FORESTS OF THE AMAZON BASIN

FOREST-SOIL TYPE	AREA (10^9 hectares)	NITROGEN INPUT LOCAL (kilograms per hectare)	NITROGEN INPUT REGIONAL (10^9 kilograms per year)
Oxisol	0.3	2.0	0.6
Ultisol	0.27	20	5.4
Varzea	0.03	200	6.0

SOURCE: E. Salati et al., "Regional Gains and Losses of Nitrogen in the Amazon Basin," *Plant and Soil* 67(1982):367–76.

FIGURE 1. Nitrogen fertilizer sales in Wisconsin, 1930–1975.



SOURCE: D. R. Keeney, "A Mass Balance of Nitrogen in Wisconsin," *Wisconsin Academy of Sciences, Arts and Letters* 67(1979):95–102.

In contrast to nitrogen losses in Wisconsin, the high proportion of nitrogen inputs lost as nitrogen gas in West Africa has clear potential for affecting balances of atmospheric trace gases at a global scale. Over 85 percent of the considerable nitrogen losses from West Africa in 1978 were in gaseous form—mainly in the form of nitrogen oxides lost during vegetation burning. Most of this burning results from land clearing in forested areas of the region as fallow successional vegetation is cleared before recropping. It thus is under direct anthropic control and may be contributing significantly to both a 0.2 to 0.4 percent annual increase in global nitrous oxide concentrations[14] as well as to the global balance of other nitrogen oxide gases. Since West African forests—where most burning in the region occurs—make up only a small percentage of total forested area in the tropics, this flux may be extremely important worldwide. Yet in most global models (see Table 1), biomass burning has been overlooked as a source of nitrogen gas emission to the atmosphere.

Implications for local agronomic management are also significant. Locally, the nitrogen that is available for loss via burning when successional rainforest is cleared—about 700 kilograms of nitrogen per hectare—is a substantial amount relative to crop uptake rates that are probably only 10 to 20 percent of this amount per year. Any management practices that could reduce this loss—by inhibiting resprouting and pests by some means other than fire and thereby leaving slash to remain on site to slowly decompose—could significantly improve the availability of nitrogen to subsequent crops.

An Emerging Challenge

Comprehensive global nitrogen models offer considerable power for resolving important questions about the impact of anthropic activities on the global environment. Two questions in particular—the effects of changes in land and fertilizer use on the rates of nitrogen oxide fluxes to the atmosphere and on the rates of nitrate losses to groundwater and coastal marine areas—would especially benefit from nitrogen models sufficiently precise to allow sensitivity analysis.

Better resolution of global models, however, awaits the development of regional budgets. It is the regional budgets that must provide the detail necessary to reduce uncertainties in the highly aggregated global model compartments. Regional models are also most appropriate for evaluating information deficiencies for specific nitrogen fluxes and for addressing environmental issues of a subglobal nature. Extending our knowledge of small-watershed nitrogen cycle processes to the larger landscape is one of the major emerging challenges of biogeochemistry.

The challenge must be met if we are to understand and perhaps attenuate our impact on the global environment. Regional scale models will play a leading role in the quantification of this impact. The need for nitrogen cycle research at regional scales is apparent as the importance of nitrogen fluxes to the health of the biosphere becomes increasingly well recognized.

TABLE 3

MAJOR NITROGEN FLUXES IN A TEMPERATE AGRICULTURAL REGION AND A DEVELOPING REGION OF THE TROPICS

	WISCONSIN		WEST AFRICA	
NITROGEN FLUX	**(10^6 kilograms per year)**	**(percent of total)**	**(10^6 kilograms per year)**	**(percent of total)**
INPUTS				
N_2 fixation				
biological	356	61	12,900	75
fertilizer	127	22	74	0.4
combustion	0	0	42	0.2
Deposition	39	7	3,900	23
Commodity imports	60	10	154	0.9
Total Inputs	**582**	**100**	**17,110**	**100**
LOSSES				
Denitrification (N_2 + N_2O)			1,140	
Leaching, erosion	341[a]	61	1,480	24
NO_x emission				
soil			159	
fire	0	0	8,340	73
combustion	0	0	41	0.4
NH_3 emission				
fertilizer	5	0.9	13	0.1
biological	130	23	208	2
Commodity exports	86	15	57	0.5
Total Losses	**562**	**100**	**11,438**	**100**

[a] Includes 61 × 10^6 kg production, 18 × 10^6 kg erosion, and 28 × 10^6 kg human waste losses

SOURCES: National Research Council, *Nitrates: An Environmental Assessment* (Washington, D.C.: National Academy Press, 1978); D. R. Keeney, "A Mass Balance of Nitrogen in Wisconsin," *Wisconsin Academy of Sciences, Arts and Letters* 67(1979):95–102; G. P. Robertson and T. Rosswall, "Nitrogen in West Africa: The Regional Cycle," *Ecological Monographs* 56(1986):43–72.

NOTES

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3. U. Rönner, "Nitrogen Transformations in the Baltic Proper: Denitrification Counteracts Eutrophication," *Ambio* 14(1985):134–38; B. J. Peterson and J. M. Melillo, "The Potential Storage of Carbon Caused by Eutrophication of the Biosphere," *Tellus*, Series B, 37(1985):117–27.

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5. NRC, note 2 above; G. P. Robertson, "Regional Nitrogen Budgets: Approaches and Problems," *Plant and Soil* 67(1982):73–80.

6. See note 4 above.

7. NRC, note 2 above.

8. E. Salati et al., "Regional Gains and Losses of Nitrogen in the Amazon Basin," *Plant and Soil* 67(1982):367–76.

9. NRC, note 2 above; D. R. Keeney, "A Mass Balance of Nitrogen in Wisconsin," *Wisconsin Academy of Sciences, Arts and Letters* 67(1979): 95–102; R. S. Ayers and R. L. Branson, eds., "Nitrates in the Upper Santa Ana River Basin in Relation to Groundwater Pollution," *California Agriculture Experiment Station Bulletin* 861(1973): 1–59; R. J. Miller and R. B. Smith, "Nitrogen Balance in the Southern San Joaquin Valley," *Journal of Environmental Quality* 5(1976):274–78; The Royal Society Study Group, *The Nitrogen Cycle of the United Kingdom* (London: The Royal Society, 1983); G. P. Robertson and T. Rosswall, "Nitrogen in West Africa: The Regional Cycle," *Ecological Monographs* 56(1986):43–72.

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11. NRC, note 2 above; Keeney, note 9 above.

12. Robertson and Rosswall, note 9 above.

13. NRC, note 2 above; Keeney, note 9 above.

14. R. F. Weiss, "The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide," *Journal of Geophysical Research* 86(1981):7185–95; M. A. K. Kahlil and R. A. Rasmussen," Carbon Monoxide in the Earth's Atmosphere: Increasing Record," *Science* 224(1984):54–56.