



Introduction

Cite this article: Fowler D, Pyle JA, Raven JA, Sutton MA. 2013 The global nitrogen cycle in the twenty-first century: introduction. *Phil Trans R Soc B* 368: 20130165. <http://dx.doi.org/10.1098/rstb.2013.0165>

One contribution of 15 to a Discussion Meeting Issue 'The global nitrogen cycle in the twenty-first century'.

Subject Areas:

environmental science

Keywords:

nitrogen cycle, nitrogen fixation, nitrification, denitrification, nitrogen deposition

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The global nitrogen cycle in the twenty-first century: introduction

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The objective of the discussion meeting at the Royal Society on 4–6 December 2011 in London, and this resulting volume was to summarize current knowledge of the global nitrogen cycle. The available literature on aspects of nitrogen cycling is extensive, but is generally specialized to components of the broad subject or to a geographical area. For example, a recent Royal Society discussion meeting was devoted entirely to nitrous oxide [1], a small but important component of the nitrogen cycle. The recent European Nitrogen Assessment and US Nitrogen Assessment [2,3] provide a thorough treatment of the science restricted to small fractions of the planet. Few attempts have been made to bring together the terrestrial, marine and atmospheric knowledge of the nitrogen cycle at a global scale as a series of review papers. Current knowledge would justify a more extensive and detailed assessment, which is beyond the scope of a single Royal Society Discussion Meeting; the 14 papers in this volume present the foundations for such a global assessment, which is currently at the planning stage.

Why now? Many processes are poorly understood and some of the major fluxes are subject to large uncertainty. Indeed, some of the major fluxes are difficult to measure directly, including the denitrification of nitrogen compounds to molecular nitrogen from terrestrial and marine ecosystems. However, it is clear that despite these uncertainties, the magnitude of human contributions to the annual total global fixation of molecular nitrogen to reactive forms (N_r) is already comparable with natural fixation. Furthermore, the consequences of the additional N_r injected into the environment from human activities include effects on global climate, human health and ecosystem function. There is therefore a pressing need to assimilate the available knowledge, to identify the known processes, sources, sinks and their effects. This compilation of current understanding identifies major gaps in understanding and shows where priorities for control measures and future research should be focused.

In choosing the scope and approach, the intention was twofold: to describe the *processes* within terrestrial and marine ecosystems and in the atmosphere responsible for transforming N_r within the major reservoirs, and transferring the compounds through the Earth system. The second objective was to quantify the *fluxes* into and between the reservoirs. The majority of the papers are independent of each other, written by different academic communities and often using different approaches. Some contributions are derived entirely from modelling activities, while others are largely derived from measurements and the synthesis of field data. The variability in approach and underpinning data and the geographical scales involved in each contribution covers a broad range. Thus, there are differences in the magnitudes of estimated fluxes and their uncertainties within the presented papers.

The approach in developing the programme for the meeting was to provide a historical perspective of the way in which our understanding of the nitrogen cycle developed, followed by a combination of papers on processes and fluxes in different ecosystems and for different classes of nitrogen compounds. The process and flux papers begin with nitrogen fixation followed by emissions to the atmosphere of oxidized and reduced nitrogen from terrestrial sources, followed by atmospheric processing of the emissions. The nitrogen cycle in

oceans and the cryosphere are then presented. The final papers in the volume provide a summary of the effects of human contributions to the global nitrogen cycle, interactions between the carbon and nitrogen cycles and a synthesis of global nitrogen fluxes and transformations at the beginning of the twenty-first century.

The chronological development of understanding of the nitrogen cycle, beginning with the discovery of the element nitrogen by Rutherford in 1772, is described by Galloway *et al.* [4]. This paper sets the context of the subsequent papers in introducing both the pathway of discovery and the motivation for use by humans of nitrogen compounds. It also provides an introduction to the consequences of human contributions to the production of N_r , much of which is generated and used in hot-spot areas of agricultural activity, transport and industry.

The natural fixation of nitrogen in soil by microorganisms represents the main natural pathway for creation of N_r and is described by Vitousek *et al.* [5] along with an estimate of the global magnitude of the annual flux. The production of nitric oxide in soil represents a source of oxidized nitrogen in the atmosphere and is important through its contribution to the production of tropospheric ozone [6]. The controls over production and emission of N_2O from soils and annual emissions are presented by Butterbach-Bahl *et al.* [7] and Bouwman *et al.* [8], respectively. Reduced nitrogen represents the other major class of N_r emitted to the atmosphere, which is very sensitive to climate, and is

described by Sutton *et al.* [9]. Organic nitrogen is widely present in the atmosphere, but is poorly understood and has been subject to little monitoring or research relative to inorganic forms. The subject is reviewed by Jickells *et al.* [10]. The removal of N_r from the atmosphere and techniques to simulate the removal in regional chemistry-transport models is described by Dennis *et al.* [11]. Modelling the transport and transport of N_r in soils and catchments en route to the sea at regional scales is described by Billen *et al.* [12], followed by a synthesis of the nitrogen cycle in the oceans [13] and in ice sheets [14]. The effects of the deposited nitrogen on terrestrial carbon budgets are an important interaction between the biogeochemical cycles of nitrogen and carbon and is explored by Zaehle [15]. This is followed by a summary of the wider consequences of human modification of the global nitrogen cycle, including effects on climate, biodiversity, human health as well as the importance of fertilizer nitrogen on crop yield [16].

The final paper by Fowler *et al.* [17] presents the global nitrogen cycle at the beginning of the twenty-first century, drawing major fluxes from the papers in this volume. It provides an indication of the likely changes in the major terms in future decades, the residence times for N_r in terrestrial and marine ecosystems and in the atmosphere. This overview of the global budget provides important perspective allowing the different components to be related, as a basis for informing future priorities for research and policy development.

References

- Thomson AJ, Baggs E, Richardson DJ. 2012 Nitrous oxide: the forgotten greenhouse gas (Papers of a Theo Murphy Meeting Issue organized and edited by AJ Thomson, E Baggs, DJ Richardson). *Phil. Trans. R. Soc. B* **367**, 1155–1277.
- Sutton MA, Howard CM, Erisman JW, Billen G, Bleeker A, Grennfelt P, van Grinsven H, Grizzetti B (eds). 2011 *The European Nitrogen Assessment: sources, effects and policy perspectives*. Cambridge, UK: Cambridge University Press.
- Davidson EA *et al.* 2013 *Excess nitrogen in the U.S. environment: trends, risks, and solutions*. Issues in Ecology report no. 15. Washington, DC: Ecological Society of America.
- Galloway JN, Leach AM, Bleeker A, Erisman JW. 2013 A chronology of human understanding of the nitrogen cycle. *Phil. Trans. R. Soc. B* **368**, 20130120. (doi:10.1098/rstb.2013.0120)
- Vitousek PM, Menge DNL, Reed SC, Cleveland CC. 2013 Biological nitrogen fixation: rates, patterns and ecological controls in terrestrial ecosystems. *Phil. Trans. R. Soc. B* **368**, 20130119. (doi:10.1098/rstb.2013.0119)
- Pilegaard K. 2013 Processes regulating nitric oxide emissions from soils. *Phil. Trans. R. Soc. B* **368**, 20130126. (doi:10.1098/rstb.2013.0126)
- Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S. 2013 Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Phil. Trans. R. Soc. B* **368**, 20130122. (doi:10.1098/rstb.2013.0122)
- Bouwman AF *et al.* 2013 Global trends and uncertainties in terrestrial denitrification and N_2O emissions. *Phil. Trans. R. Soc. B* **368**, 20130112. (doi:10.1098/rstb.2013.0112)
- Sutton MA *et al.* 2013 Towards a climate-dependent paradigm of ammonia emission and deposition. *Phil. Trans. R. Soc. B* **368**, 20130166. (doi:10.1098/rstb.2013.0166)
- Jickells T, Baker AR, Cape JN, Cornell SE, Nemitz E. 2013 The cycling of organic nitrogen through the atmosphere. *Phil. Trans. R. Soc. B* **368**, 20130115. (doi:10.1098/rstb.2013.0115)
- Dennis RL, Schwede DB, Bash JO, Pleim JE, Walker JT, Foley KM. 2013 Sensitivity of continental United States atmospheric budgets of oxidized and reduced nitrogen to dry deposition parametrizations. *Phil. Trans. R. Soc. B* **368**, 20130124. (doi:10.1098/rstb.2013.0124)
- Billen G, Garnier J, Lassaletta L. 2013 The nitrogen cascade from agricultural soils to the sea: modelling nitrogen transfers at regional watershed and global scales. *Phil. Trans. R. Soc. B* **368**, 20130123. (doi:10.1098/rstb.2013.0123)
- Voss M, Bange HW, Dippner JW, Middelburg JJ, Montoya JP, Ward B. 2013 The marine nitrogen cycle: recent discoveries, uncertainties and the potential relevance of climate change. *Phil. Trans. R. Soc. B* **368**, 20130121. (doi:10.1098/rstb.2013.0121)
- Wolff EW. 2013 Ice sheets and nitrogen. *Phil. Trans. R. Soc. B* **368**, 20130127. (doi:10.1098/rstb.2013.0127)
- Zaehle S. 2013 Terrestrial nitrogen–carbon cycle interactions at the global scale. *Phil. Trans. R. Soc. B* **368**, 20130125. (doi:10.1098/rstb.2013.0125)
- Erisman JW, Galloway JN, Seitzinger S, Bleeker A, Dise NB, Petrescu AMR, Leach AM, de Vries W. 2013 Consequences of human modification of the global nitrogen cycle. *Phil. Trans. R. Soc. B* **368**, 20130116. (doi:10.1098/rstb.2013.0116)
- Fowler D *et al.* 2013 The global nitrogen cycle in the twenty-first century. *Phil. Trans. R. Soc. B* **368**, 20130164. (doi:10.1098/rstb.2013.0164)