Perspective

Nitrogen in the environment: inequalities and our changing relationship with nitrogen

Carly J. Stevens

Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ. Email: c.stevens@lancaster.ac.uk

Anthropogenic activities have greatly perturbed the global nitrogen (N) cycle. Planetary boundaries, which describe a safe operating space for humanity, have already been exceeded for the N cycle (*1*). In some parts of the world the environment has been effected by excess N, with negative impacts on biological diversity, human health and climate. However, in other parts of the world shortages of N mean that food needs cannot be met. Nitrogen is an abundant element on earth, it makes up 78.1% of our atmosphere and is an essential nutrient for all forms of life. Much of this N is in the form of N_2 gas and is unreactive and not available for use by the majority of living organisms but a portion of it, fixed by natural or man-made processes including the Haber-Bosch process, is in a reactive form (Nr – including NO_y, NH_x, N_20, HNO_3 and other organic and inorganic forms) available for use by living organisms. Over the last century the amount of Nr from anthropogenic activities has increased to such an extent that it now exceeds natural fixation and has more than doubled global cycling of N (anthropogenic 210 Tg N yr^{-1}, natural 203 Tg N yr^{-1}) (*2*). As a consequence of this increase in the fixation of N, N has become a major cause for concern in many parts of the world, polluting air, water and soil (Figure 1).

A major cause of N pollution in the developed world is food production. Pollutant Nr, released to the environment during food production and consumption, stems from a range of issues including the over-use of relatively low-cost fertilisers, poor management of animal wastes, over consumption of protein and food waste. Between 1961 and 2007 both N inputs and grain yields increased globally but, the amount of added N recovered in the harvested crops remained relatively unchanged at around 40%. This means that the amount of N lost to the environment has steadily increased. However, there are considerable inequalities in N use globally. Countries outside the OECD and in the major emerging economies the amount of N recovered in crops remains low. Not only are there nutrient deficiencies but the nutrients that are available are often used inefficiently (*3*). Sub-Saharan Africa provides a perfect example. Here, nutrient poor soils were yielding an average of 1 t ha^{-1} for grain crops in 2012, with fertiliser use averaging 9 kg ha^{-1} of cultivated land. By contrast, in Asia, crop yield reached 4.5 t ha^{-1} but this was achieved with fertiliser application averaging 96 kg ha^{-1} (*4*). Shortages of N clearly lead to large problems in meeting population demands for food, but these problems are just as intractable as the problems N pollution causes in other parts of the world.

One of the major consequences of increased reactive N availability has been an increase in atmospheric deposition of Nr. Between 1900 and 1980 levels of oxidised N deposition in Europe increased by 3-4 times whilst reduced N doubled (*5*). The concentrations of N in plant tissues, often been considered an indicator of N status, declined between 1980 and 2017, despite globally increasing availability of Nr. Examining 38,646 terrestrial plant samples collected from areas that had not received any fertiliser input, Craine et al. (*6*) found global declines in foliar N concentrations. The reduction in N content seems to indicate oligotophication rather than eutrophication, i.e. there is less N available for the plants than there was in the past. Whilst there have been declines in deposition in some developed countries since 1980 this is not a global trend making this depletion of plant N reserves hard to reconcile with increased Nr emissions. The authors suggest that this is caused by increased levels of CO_2 and longer growing seasons, which allows greater levels of biomass production. The authors also observe a decline in $\delta^{15}N$, although data are highly variable and changes are small. Since stable isotopes are measured as a ratio of the heavy and light isotopes in a sample, and atmospherically deposited sources of N would typically be light (the so-called 'Haber-Bosch effect' (*7*)), the observed decline in $\delta^{15}N$ may therefore indicate increased atmospheric deposition. Indeed, a recent modelling study has indicated increases in isotopically light N in global oceans (*7*), confirmed by a study of coral at a remote reef (*8*). Combined with the global deposition trends, this would suggest that Craine's findings (*6*) may be even more pressing because the declines in plant N concentration are occurring despite a signal of increasing atmospheric deposition.

Craine et al. (*6*) use the results to question whether humanity has exceeded a true planetary boundary for N availability because plant tissue N is falling. However, the extensive damage done to ecosystems supports the argument that we have indeed exceeded a planetary boundary. Atmospheric deposition of N has become a major driver of plant productivity globally (*9*) and is an important driver of species richness and composition at a continental scale (*10*). Considerable damage has already been done and many field experiments with simulated deposition have demonstrated considerable inertia in the recovery of soil chemistry and species composition when levels of N addition are reduced. For example, in an alpine grassland in the Rocky Mountains, USA, 12 years of simulated Nr deposition had resulted in significant changes in species composition, including the decline of a previously dominant sedge and increases in other species. The study also found changes in fungal to bacterial ratio, nitrification in the soil, soil pH, toxic metal concentrations and cation concentrations. Nine years after applications of N were ceased many of these soil variables had not returned to baseline levels and nor had biota (*11*). This type of finding is not uncommon and it is possible, given the lack of recovery observed in some communities, that alternative stable states may have been reached in some habitats.

Realisation of the extent of the damage caused by N deposition together with co-benefits from other areas of environmental policy is beginning to result in reductions in emissions and deposition of N. Deposition of oxidised N peaked in Europe in the 1980s and has since declined but there have been much smaller declines in reduced N deposition (*5*). Similar trends have been observed in the USA with recent reductions in deposition driven by reductions in emissions of oxidised N (*12*). However, if we are to reduce the creation of Nr further we need wide ranging changes to agricultural practices and our attitude to food. A recent paper highlighted the environmental pressures that the food production system places on the environment and the need to make changes to our diet, combined with technological improvements and reductions in food waste, if we are to stay within planetary boundaries, including the boundary for N. The paper includes scenarios around dietary change towards a healthier plant-based dietary pattern and not exceeding global dietary guidelines (*13*). Meat consumption is particularly important in terms of driving our N footprint because of the large amounts of Nr lost to the environment during meat production. Interestingly, in some countries, our relationship with N in our diet is already beginning to change, whether we are aware of it or not. Globally meat consumption continues to grow but there is some evidence that in some high-income countries meat consumption per capita is beginning to decline (*14*).

Our N cycle has been hugely perturbed at a global scale and there is an urgent need to address the problem of excess Nr in our environment. There are many potential approaches that can be taken such as technical solutions to agricultural and industrial emissions and changes in practice in polluting sectors, but these need to be widely adopted and supported with legislative limits. There is also a need to address the lack of Nr in many regions of the world to ensure that food production is sufficient to meet requirements. This is a complex problem with many societal considerations and there is considerable debate around the role inorganic fertilisers should play (*4*). Balancing these two contrasting issues presents a big challenge to the communication of Nr as an environmental problem to the public and is one which can only be addressed through interdisciplinary collaboration between a range of scientists, social scientists, governments and non-governmental organisations. Nr excesses and shortages are set to continue to be major environmental issues into the future so increasing awareness, changing behaviours and increasing regulation, particularly to reduce N emissions, must all come together to address this global problem.

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Figure 1. Problems associated with excess and insufficient nitrogen in terrestrial systems. Information on the probnlems associated with insufficient nitrogen is based on (*3*).