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COMMENT

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Applying liquid manure more precisely than this would be cleaner, reduce odour and emit less ammonia.

Too much of a good thing

Curbing nitrogen emissions is a central environmental challenge for the twenty-first century, argue **Mark Sutton** and his colleagues.

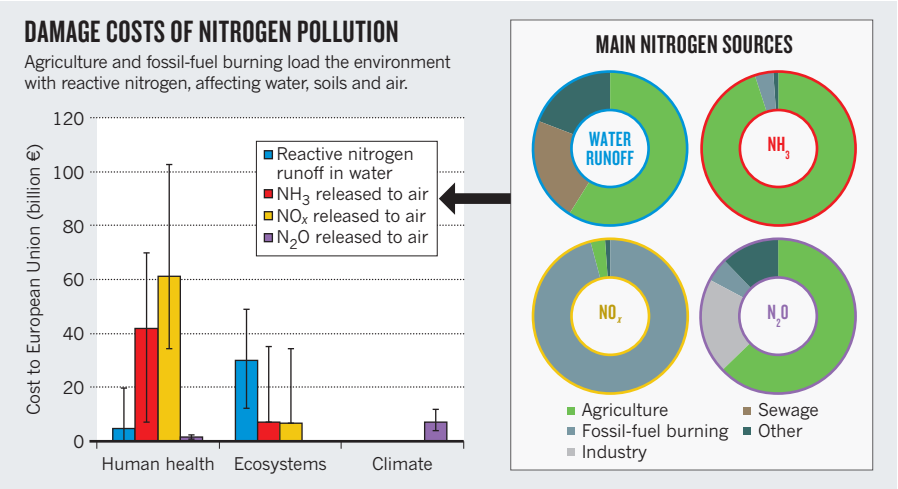
An analysis published this week calculates that excess nitrogen in the environment costs the European Union (EU) between €70 billion (US$100 billion) and €320 billion per year[1]. It is the first time that an economic value has been placed on the threats posed by nitrogen pollution, including contributions to climate change and biodiversity loss. To put that into perspective, this cost is more than double the value that nitrogen fertilizers are estimated to add to European farm income.

This economic valuation is just one outcome of the five-year European Nitrogen Assessment, which has drawn together 200 experts, including ourselves, to understand the sources, processes and impacts of nitrogen as a basis to inform policy.

Excess reactive nitrogen threatens the quality of air, soil and water. It affects ecosystems and biodiversity, and alters the balance of greenhouse gases. Existing climate and air-pollution policies that aim to reduce energy consumption and fossil-fuel burning, such as the Gothenburg Protocol, are helping to cap nitrogen emissions ▶

SUMMARY

- Nitrogen pollution costs the European Union between €70 billion and €320 billion per year.
- Policies should address farming, meat consumption, use of human sewage and fossil-fuel burning.
- The Gothenburg Protocol is an opportunity to further reduce emissions.
- A global inter-convention nitrogen protocol is needed.



from transport and industry. Together with policies on nitrates in drinking water and reductions in cattle numbers, these have led to a modest drop in European nitrogen pollution since the 1980s.

But existing policies are piecemeal, and there has been little attempt to integrate the effects of the different nitrogen threats. Nitrogen pollution poses an even greater challenge than carbon, because the element has many complex effects as it cascades through many chemical forms. There is a need for new policies that cover these concerns and encourage changes in farming, diet and even what we do with human waste.

THE DAMAGE DONE

Nitrogen can be divided into two classes. Unreactive nitrogen (N_2) makes up 78% of Earth's atmosphere. Reactive nitrogen includes every other form of the element, including nitrogen oxides (NO_x), nitrous oxide (N_2O), ammonia (NH_3) and nitrate (NO_3). All biological systems need reactive nitrogen, but historically it has been in short supply. Until the end of the nineteenth century, the main agricultural source was fixation of N_2 by symbiotic bacteria in legumes planted for that purpose, combined with careful recycling of the limited amount of nitrogen in manure.

By 1900, there was a worrying shortage of reactive nitrogen, as fertilizers were needed to feed a growing population and nitrogen-based explosives were wanted for weaponry. The solution came in 1908 with the Haber–Bosch process, allowing cheap ammonia to be made from N_2 and energy on an industrial scale. This process was so successful that, within a century, human production of reactive nitrogen had more than doubled global rates of nitrogen fixation. Without it, around half of humanity would not be alive[2]. As an intentional strategy to address the world's shortage of reactive nitrogen, the Haber–Bosch process is arguably the greatest single experiment ever made in geoengineering.

But the mass production of reactive nitrogen has come with costs. Nitrogen-based explosives killed 100 million people in armed conflicts during the twentieth century[2]. Their use in mining has opened up fossil-fuel reserves, the burning of which has released carbon dioxide and more reactive nitrogen into the atmosphere. About half of the nitrogen added to farm fields in Europe ends up as pollution, or is wasted by denitrification back to N_2 (ref. 1).

In water, excess reactive nitrogen causes algal blooms that can kill fish, and nitrate in drinking water can harm human health, increasing the risk of bowel cancer. About 80% of European fresh waters exceed a threshold for high risk to biodiversity of 1.5 milligrams of nitrogen per litre. Combined with the effects of too much phosphorus, the resulting proliferation of algae in coastal areas gives new meaning to the idea of 'green' bathing.

In the air, reactive nitrogen adds to particulate matter and ground-level ozone, created when nitrogen oxides react with organic compounds, causing respiratory and cardiovascular disease. The effects of airborne particles take six months off the life expectancy of at least half of all Europeans. In forests, ammonia pollution encourages the growth of algal slime that can suffocate tree-living plants such as mosses and lichens (see picture) to such an extent that it would be easy to think this were natural in agricultural areas of northwest Europe. The assessment estimates that NH_3 and NO_x emissions have reduced forest biodiversity by more than 10% over two-thirds of Europe. Nitrogen deposition also threatens the ability of peatlands to store carbon by killing the bog-building moss *Sphagnum*.

Importantly, we now have a first estimate of how the different climate warming and cooling effects of nitrogen add up across Europe. Nitrogen tends to warm the planet by forming N_2O and ground-level ozone, both of which are powerful greenhouse gases. At the same time, nitrogen emissions tend to cool the planet: by reducing the atmospheric life-time of methane; by forming particulate matter that reflects light back into space; and by acting as a fertilizer, increasing the growth of forests. Overall, the assessment finds that these effects tend to balance out. Efforts need to focus on reducing the warming effects, while recognizing that the adverse effects of particulate matter and nitrogen deposition on human health and biodiversity may more than outweigh their climate benefits.

COSTS AND BENEFITS

It is hard to tally up all the costs and benefits of reactive-nitrogen production. The direct and indirect effects influence everything from population growth and energy production to the manufacture of nitrogen-based products such as nylon, polyurethane and hydrazine rocket fuel.

The benefits of nitrogen can be seen from its largest use: agricultural fertilizers. Manufactured fertilizer adds 11 million tonnes of reactive nitrogen annually to fields in the EU. This produces a direct benefit to European farmers, in terms of crops grown, of €20 billion to €80 billion per year, when the long-term benefits are included[1]. On top of that, biological fixation and recycled sources of nitrogen — including plant residues, animal manures and atmospheric deposition — add 17 million tonnes, giving a total direct benefit of €25 billion to €130 billion, even before value is added during the food-supply chain.

But half of the nitrogen in fertilizers and manures is lost to the surrounding environment. In economic terms, this amounts to a loss of potential benefits to farmers of €13 billion to €65 billion per year. On these grounds alone, there is a strong case for using nitrogen more efficiently.

> ***"The effects of airborne particles take six months off the life expectancy of at least half of all Europeans."***

These numbers, however, are much lower than the estimated cost of the damage from reactive-nitrogen emissions. The assessment gauges these costs by looking at society's readiness to pay for longer and healthier life, for nature restoration, or for climate stability. The grand total of €70 billion to €320 billion per year is equivalent to 1–4% of the average disposable per capita income of European citizens.

Of the total cost of damage from reactive-nitrogen emissions, 75% comes from the effects of NO_x and NH_3 on human health and ecosystems. The effect of N_2O emissions on climate warming accounts for only around 5%. Although N_2O has recently been heralded as the main cause of stratospheric ozone depletion[3], this represents only 1% of the damage costs. Climate change and ozone

thinning are important, but the threats to health and ecosystems are an even stronger argument for taking action on nitrogen.

Clearly nitrogen is one of the major environmental challenges of the twenty-first century.

Although better combustion and energy technologies can reduce nitrogen emissions from fossil fuels, further efforts must curb the increasing use of energy and transport. We also need a radical rethink of sewage systems, which waste reactive nitrogen, using yet more energy to turn it back to N_2. The technology is available to recycle sewage nitrogen, but it needs development[4]. Such a major change is certainly possible, as shown by nineteenth-century Paris, where more than half of the nitrogen in sewage was recycled, including in the manufacture of ammonium sulphate fertilizer on an industrial scale[1]. One approach would be to use sewage to make biogas, leaving a useful residue rich in nitrogen and phosphorus.

But the largest challenges are to manage nitrogen better in agriculture and to moderate Europeans' consumption of animal protein. Amazingly, livestock consume around 85% of the 14 million tonnes of nitrogen in crops harvested or imported into the EU; only 15% is used to feed humans directly[1]. European nitrogen use is therefore not primarily an issue of food security, but one of luxury consumption. If Europeans obtained all their protein from plants, only 30% of the crops grown currently would be needed, reducing nitrogen fertilizer inputs and the associated pollution by 70%.

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Ammonia can kill tree-living plants (left), replacing them with algal slime.

DRIVING CHANGE

The average EU citizen now eats much more meat and milk than is needed for a healthy diet[1]. Reducing meat and dairy consumption could therefore benefit the health of many people and help protect the environment at the same time. Recognizing this, in 2009 some of the authors of this piece developed the 'Barsac Declaration', through which many of the assessment authors have committed to fostering the 'demitarian diet'[5], making it easier to choose half-portions of meat. Such initiatives have a huge potential to change dietary aspirations in a world where per-capita meat consumption is rapidly increasing.

There are many ways to reduce nitrogen losses from agriculture. Improving the production potential of crops and livestock can help, and covers on manure storage tanks and low-emission techniques for spreading fertilizers and manure are essential. At present, most liquid manure is spread with a crude spraying method that dirties the crop and maximizes NH_3 emissions. Applying manure in bands cuts emissions by 30–60%, decreases odours, leaves the crop clean and reduces the farmer's fertilizer bill. By improving nitrogen-use efficiency in this way, measures to decrease NH_3 emissions turn out to be central to reducing overall N_2O emissions.

Experience shows that regulatory or financial drivers are needed to ensure such technologies are used. Changes need not be uneconomic. The Netherlands and Denmark have required low-emission techniques for more than a decade, yet livestock farming in these countries remains among the most competitive in Europe.

At present, no single United Nations (UN) convention can handle all the threats posed by reactive nitrogen. An inter-convention protocol is needed. This could, for example, link the UN Framework Convention on Climate Change and the Convention on Biological Diversity with the Air and Water Conventions of the United Nations Economic Commission for Europe (UNECE).

In the short term, there are already opportunities on the table for Europe. The UNECE Air Convention — also known as the Convention on Long-range Transboundary Air Pollution — is currently renegotiating its Gothenburg Protocol, which caps national emissions of air pollutants. Like the update of the Kyoto Protocol, this is happening slowly: talks began in 2007. Further reductions in NO_x emissions will surely be agreed. The big question is how far the parties will commit to reducing NH_3 emissions.

The air convention's Task Force on Reactive Nitrogen has recently shown that preventing NH_3 release is much cheaper than previously estimated, especially once the fertilizer savings are considered. Scaling up these numbers shows that cutting NH_3 emissions across the EU by 20% would cost less than €500 million per year[6]. On the basis of total NH_3 damage costs of €15 billion to €105 billion per year (see graphic), the environmental benefits of mitigation are therefore around 20 (range of 6 to 42) times the costs, even without counting the other benefits this gives in reducing N_2O emissions and nitrogen runoff.

Given the political sensitivity of the agricultural sector, however, the case for reducing NH_3 emissions is likely to depend on demonstrating the broader impact of better nitrogen management. This challenges the scientific community to continue quantifying the benefits of nitrogen mitigation. Now that a first effort has been made for Europe, a global assessment of nitrogen is urgently needed, as called for by the International Nitrogen Initiative in their 2010 Delhi Declaration[7].

At the same time, the policy community must develop more joined-up approaches. If parties to the Gothenburg Protocol, for example, are to agree serious commitments to reducing NH_3 and NO_x emissions, they will need a motivation that can only come from seeing the bigger picture. They should be jumping at the chance that reducing NH_3 and NO_x emissions could help meet their existing N_2O and NO_3 commitments. Such ideas point to a vision for better nitrogen management where air, soil, water, climate and biodiversity can all benefit. ■

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