C Sustainable nutrient management

Abstract / summary

Inputs of nitrogen (N) and phosphorus (P) are crucial for food production but inherent inefficiencies in crop and livestock production imply that much of those are lost to the environment. This results in multiple pollution threats, such as dead zones in coastal oceans, harmful algal blooms, terrestrial and aquatic biodiversity loss, nitrate contamination of drinking water and climate change. WIMEK's research on sustainable use of nutrients aims at providing solutions towards nutrient circularity in agriculture by: (i) developing (global) nutrient flow and impact models across different scales (landscapes, water basins, countries, continents and world), (ii) developing sustainable nutrient removal, recovery and reuse technologies and (iii) governance of nutrient management. By applying multidisciplinary research methods, new integrated concepts are developed towards closing the gap between current and environmentally acceptable nutrient inputs while ensuring or even enhancing food production. We work in close cooperation with stakeholders, ensuring that our science is used both by policy makers and farmers to solve the world's challenge to feed 10 billion people by 2050 sustainably.

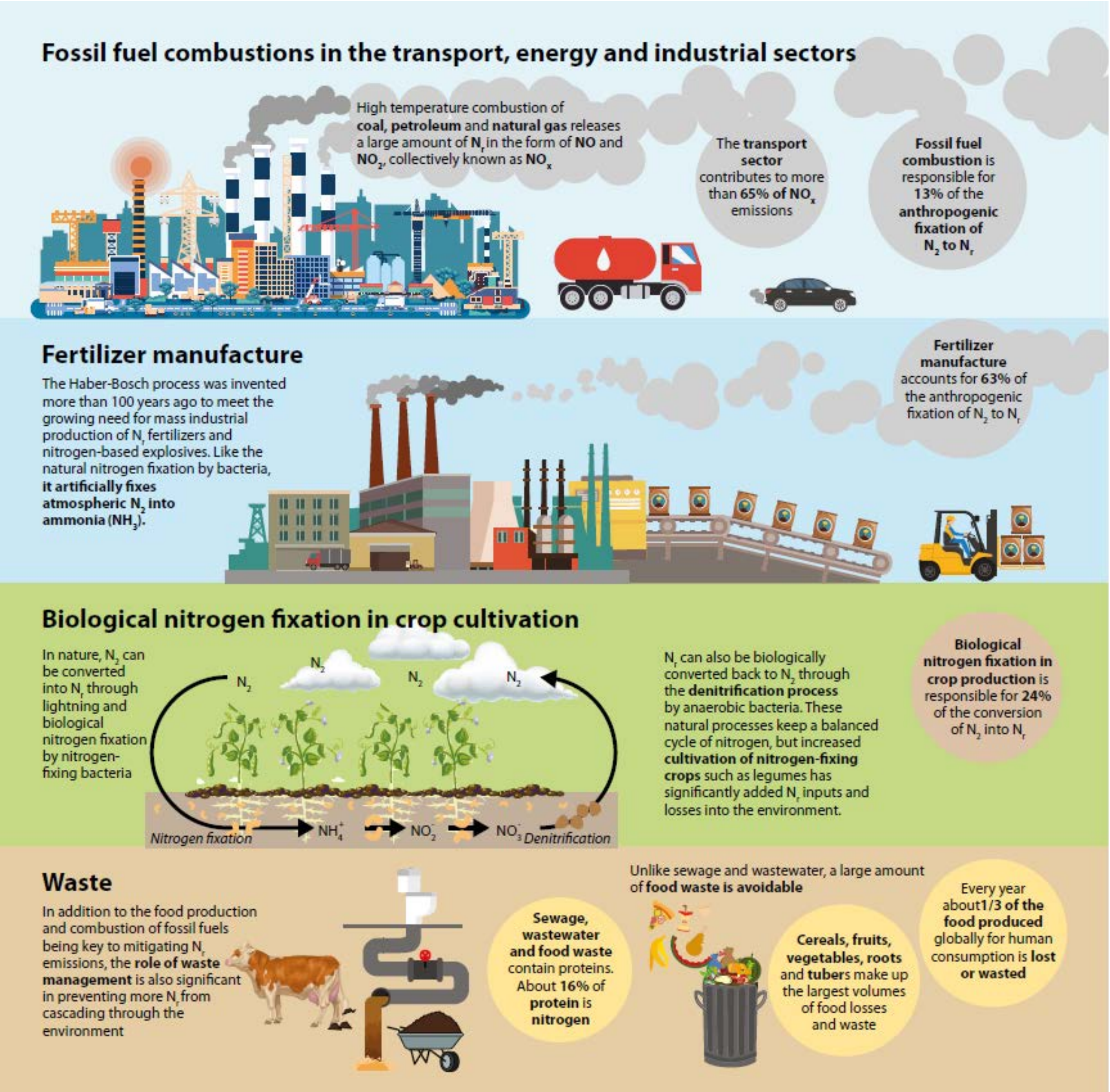

Figure 1: Nitrogen fixation and nitrogen flows (taken from Sutton et al., 2019)

Background

Sustainable use of nutrients, with a focus on nitrogen (N) and phosphorus (P) is at the core of several Sustainable Development Goals. Food security depends on inputs of N and P. Inputs by biological N fixation and by mineral and organic fertilizer application is, however, highly unevenly distributed on a global scale, ranging from N and P inputs that are inadequate to maintain soil fertility in many developing countries to excessive surpluses in many developed and rapidly growing economies. Nutrient-limited regions include much of Africa, Latin America and South East Asia, where too low levels of available N and P limit food production, also leading to depletion of soil nutrient stocks, posing risks of land degradation. However, in other regions, such as Western Europe, US and China, there is ample use of N and P fertilizers to increase crop yields, but the inherent inefficiencies in crop and livestock production implies that much of the N and P inputs to food production are lost to the environment. Together with N emissions from traffic and industry (Figure 1), this results in multiple pollution threats, such as dead zones in coastal oceans, harmful algal blooms, terrestrial and aquatic biodiversity loss and health impacts by nitrogen in particulate matter nitrate contamination of drinking water (Figure 2, 3). In addition, nitrogen use also affects climate change, amongst others by the warming impact of enhanced nitrous oxide (N_2O) emissions and the cooling impact of increased productivity and carbon (C) sequestration in terrestrial and marine ecosystems.

In view of multiple impacts of N and P use, 'planetary boundaries' have been proposed for the intentional chemical N fixation from the atmosphere and for the mining of P for the use of N and P fertilizers. However, these boundaries do not well account for the spatial variation in nutrient problems over the world, nor do they link well to the need for food security. In many parts of the world, an increase in N and P input is needed, while in other parts N and P application need to be reduced, with the challenge to maintain or even enhance yields and reduce environmental impacts.

Research objectives

WIMEK is involved in a suite of research lines that contribute to sustainable nutrient management with multidisciplinary and transdisciplinary research objectives, linking expertise from different disciplines to create scientific and societal impact. This includes the assessment and modelling of (i) the fate and effects of nutrient flows in agricultural systems, air, freshwater-, marine and terrestrial systems across different scales (landscapes, water basins, countries, continents and world), (ii) the overall impact of nitrogen use on greenhouse emissions, (iii), regional boundaries for nitrogen losses, surpluses and inputs, (iv) required increase in nutrient use efficiencies to reconcile food production and regional boundaries for agricultural nitrogen inputs (most within WIMEK's Climate, Water and Society (**CWS)** cluster). Other research lines include (v) the removal, recovery and reuse of nutrients from waste water (**ETE**) and (vi) the governance of nutrient management for food production and its trade-offs with the provisioning of water and energy in urban areas (**ENP**) and (vii) the evaluation of policy options for stimulating organic waste applications on nutrient losses by integrating spatial agent-based models (LSP) with soil-carbon-and-nutrient-cycling models (ESA).

Below three examples are given on specific research objectives, i.e.

- Integrated nitrogen impact analysis at environmental systems analysis (ESA) group ; read more. This includes the integrated impacts of nitrogen use on soil quality (acidification), air quality (ammonia and nitrous oxide emissions) and water quality (nitrate runoff and leaching) with related impacts on crop yields, biodiversity and forest growth and the related assessment of critical nitrogen losses and inputs in view of those impacts with a focus on EU27, China and the world (papers 1-7).
- integrated modelling of nutrient flows in aquatic and terrestrial systems at the Water Systems and Global Change (WSG) Group; read more. This includes the assessment of impacts of agricultural and waste water nutrient management on the export of dissolved (inorganic and organic) and particulate N and P by rivers to coastal seas with a focus on China and the world (papers 8-10).
- removal, recovery and reuse of nutrients from wastewater at the Environmental Technology (ETE) Group read more. This includes the development of methods for recovering N and P from domestic wastewater, which could satisfy a quarter of the present worldwide P fertiliser use (papers 11-13).

Research approach

WIMEK performs multidisciplinary research by focusing simultaneously on the environmental, technological, and social challenges to feed 10 billion people by 2050 sustainably. In this context comprehensive and integrated modeling of the nutrient flows on land, in air and in water, affecting soil, air and water quality, is a key foundation of our understanding of the impacts of nutrient flows at various scales. This is essential to identify the main causes of nutrient losses and their related impacts, and to evaluate the effectiveness of interventions. The modelling approaches are used to support spatially-explicit policies to improve nutrient management, whereas scenario analyses are used to assess the potential impacts of changes in socio-economic development, combined with the implementation of technological interventions.

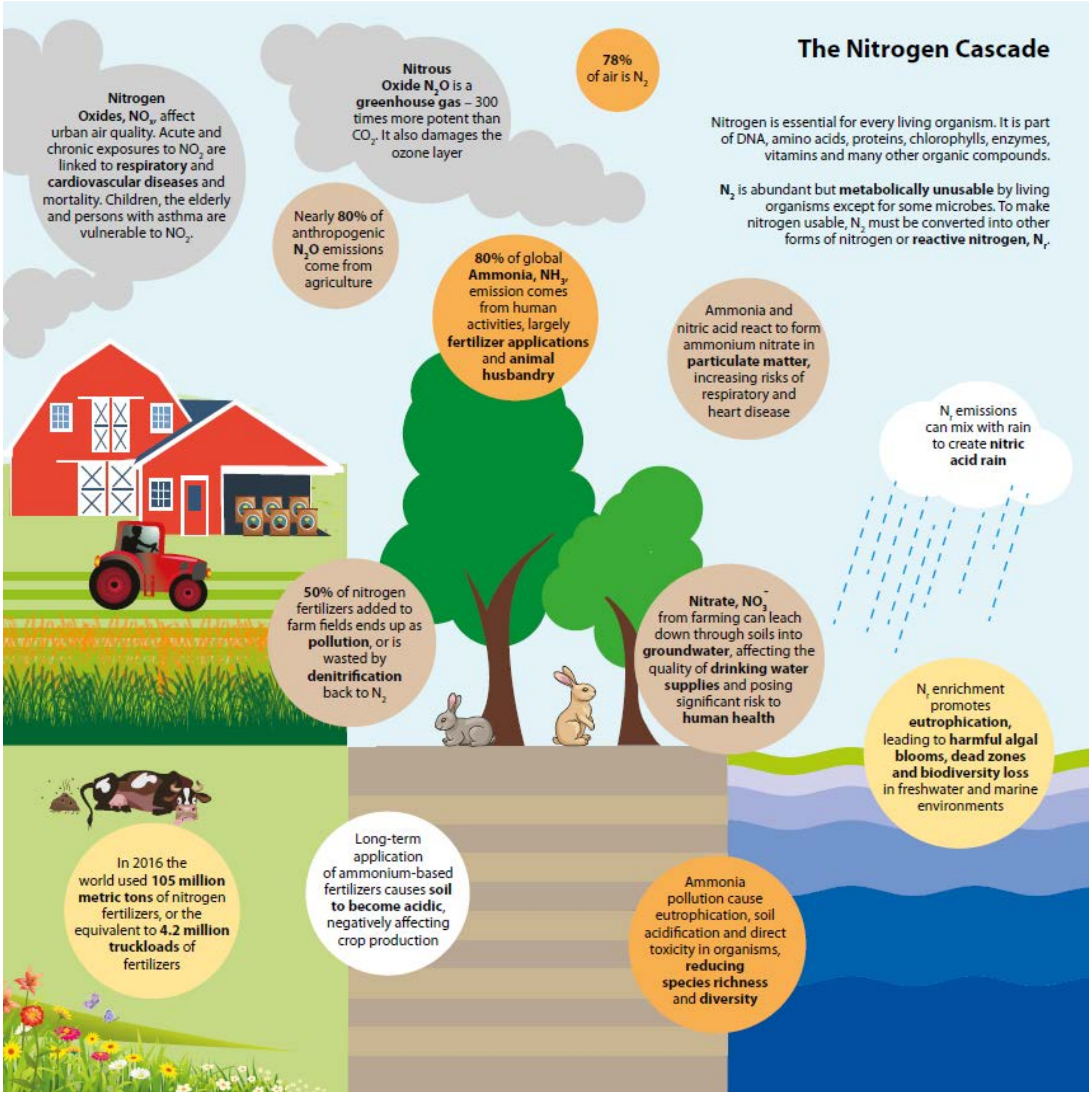

Figure 2: the Nitrogen cascade (taken from Sutton et al., 2019

Both the Integrated nitrogen impact analysis and the integrated modelling of nutrient flows is carried out with a focus on China in view of the high potential to reduce N and P inputs in this country in various programmes and projects, including the:

- WUR-CAU AGD Programme
- PhD project Agricultural Green Development for integrated nitrogen management of air and water in Quzhou and North China Plain; read more
- PhD projects on Modelling past, present and future nutrient flows from land to sea in China: using the MARINA familiy of models; read more

Stakeholder involvement

The work of WIMEK has had clear scientific and societal impacts. In terms of science the work has resulted in a large number of papers in prestigious journals and many of these papers are highly cited. The work is also highly valued by research funders showing the large number of research grants supporting this work. The research is performed in close collaboration with relevant stakeholders, including government regulators, environmental agencies (GPA, EEA) fertilizer industries (International Fertilizer Association, Fertilizers Europe), farmer organizations (LTO). This guarantees that research results are used in policymaking, fertilizer management and farm management, all contributing to a more sustainable management of nutrients. The WIMEK researchers also participates in the coordination of several Networks, including:

- INMS: Towards the Establishment of an International Nitrogen Management System
- WWQA: World Water Quality Alliance
- CDM: Commissie van Deskundigen Meststoffenwet

Figure 3: Multiple pollution threats of Nitrogen

Link to education

WIMEK is active in providing education on sustainable nutrient management. We teach students the impacts of nutrient management on agricultural production and on the environment in terms of air, soil and water quality and thereby on health, climate and nature. We teach them the use of various (chains of) models and modelling approaches to evaluate the effects of policy scenarios and management options on the environmental quality and related impacts. We engage them in modelling tools that can be used support managers (e.g. farmers or foresters) or policy/decision-makers in taking appropriate management or policy measures.

Research Highlights

Sustainable nutrient management is related to all three Grand Challenges of WIMEK, i.e.: climate action, managing our future biosphere and advancing circular systems. WIMEK researchers have produced several WoS highly cited research papers in high impact journal, that also attained press attention, on these topics. Examples of highlights are

- *Climate action:* A combination of several studies showed that at global scale the estimated CO_2 uptake due to N inputs to terrestrial, freshwater and marine ecosystems largely (on average near 75%) compensates the stimulating effect on direct and indirect N2O emissions. However, this effect is partly reduced by NOx-induced O3 exposure, which reduces CO_2 uptake, thus implying a compensation near 60%[1]. On European scale the N induced CO_2 compensation is likely higher[2]. However, on the long term, effects on ecosystem CO_2 sequestration are likely to diminish due to growth limitations by other nutrients such as phosphorus[3] and there are amplifying effects of Earth system interactions[4]. These insights affect sustainable management of both agriculture and forests

- *Managing our biosphere:* Various studies show that a reduction in N losses and related N inputs near 50% is needed at global and at EU scale. Highly cited papers in high impact journals present those results in terms of a planetary boundary for P inputs[5], N surplus[6] and N inputs[7], as compared to current inputs and surpluses. The needed reduction of 50% is now mentioned in several policy documents including the Colombo declaration on sustainable nitrogen management for the world and the Green deal for Europe.
- *Advancing circular systems:* A study that assessed integrated approaches to meet food demand in 2050 within planetary boundaries of, amongst others, nitrogen and phosphorus showed that: (i) the environmental impact of food production will increase by 50 to 90 percent until 2050 in a business as usual scenario and (ii) only a combination of diet change, waste reduction, circular agriculture and new sustainable technologies with high ambition can reverse this trend to impacts below the current level (Springmann et al., 2018).

Impact

The nutrient research has large societal impacts both in the Netherlands and worldwide. This holds for example for the research on the potential to feed the world sustainably in 2050, which got ample press attention[1,2] with related presentations[3,4] for e.g. public and food companies interview[5]

The large attention for the "Integrated nitrogen impact analysis" research is related to the Dutch 'nitrogen crisis', where a high court ruled that the government needs to take immediate action to reduce NH3 and NOx emissions to reverse widespread transgression of critical loads on natural ecosystems. WIMEK researchers estimated that N emissions have to be reduced by 50% and 80%, respectively, to protect 75% and 95% of all Dutch Natura 2000 sites. This research result was included in an advice to the Dutch government by a policy advisory board.

The research is explained to te broader public on various websites such as: WUR dossier Nitrogen, https://www.biomaatschappij.nl/online-dossier/dossier-stikstof/ and The nitrogen problem explained. Furthermore, the research results on nitrogen and the potential to solve the problem is not only communicated to policymakers, but also to the business community, banks and the general public, by interviews in newspapers, radio and TV in the Netherlands (and foreign channels in e,g. Belgium, Germany and the UK. For the combination of innovative research and research communication, an award nomination has been made: Nitrogen expert Wim de Vries nominated for Huibregtsen award 2020

1 https://www.ad.nl/wageningen/mondiale-studie-10-miljard-mensen-duurzaam-voeden-is-mogelijk~a744bf16/

2 https://www.volkskrant.nl/kijkverder/2018/voedselzaak/artikelen/zo-voeden-we-die-10-miljard-monden-in-2050-met-behoud-van-de-aarde/

3 https://www.foodlog.nl/artikel/en-hoe-voeden-we-die-10-miljard-monden-dan/

4 https://www.fondation-louisbonduelle.org/en/2019/11/22/sustainably-feed-10-billion-people-2050/

5 https://www.fondation-louisbonduelle.org/en/2019/12/30/conference-2019-interview-wim-devries/

References

1 De Vries, W., M. Posch, D. Simpson and G. J. Reinds, 2017a. Modelling long-term impacts of changes in climate, nitrogen deposition and ozone exposure on carbon sequestration of European forest ecosystems. Science of the total Environment 605-606: 1097–1116.

2 De Vries, W., E. Du, K. Butterbach Bahl, L. Schulte-Uebbing and F. Dentener, 2017b. Global-scale impact of human nitrogen fixation on greenhouse gas emissions. Oxford Research Encyclopedia of Environmental Science. doi 10.1093/acrefore/9780199389414.013.13.

3 De Vries, W., 2014. Nutrients trigger carbon storage. Nature climate change 4: 425-426.

4 Lade, S.J, W. Steffen, W. de Vries, S.R. Carpenter, J. F. Donges, D. Gerten, H. Hoff, T. Newbold, K. Richardson and J. Rockström, 2020. Human impacts on planetary boundaries amplified by Earth system interactions. Nature Sustainability 3: 119–128

5 Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, A. Wood, F. DeClerck, M. Jonell, M. Clark, L. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J.A. Rivera, W. de Vries, L.M. Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S.E. Cornell, S. Reddy, S. Narain, S. Nishtar and C.J.L. Murray, 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393(10170): 447-492.

6 Springmann, M., M. Clark, D. Mason-D'Croz, K. Wiebe, B.L. Bodirsky, L. Lassaletta, W. de Vries, S.J Vermeulen, M. Herrero, K.M. Carlson, M. Jonell, M. Troell, F. DeClerck, L.J. Gordon, R. Zurayk, P. Scarborough, M. Rayner, B. Loken, J. Fanzo, H.CJ. Godfray, G.D. Tilman, J. Rockström and W. Willett, 2018. Changes in food management, technology and diets to stay within planetary boundaries. Nature 562: 519–525.

7 Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, S. Sörlin, 2015. Planetary Boundaries: Guiding human development on a changing planet. Science 347, 1259855 (2015). DOI: 10.1126/science.1259855.

8 Strokal M, Kroeze C, Wang M, Bai Z, Ma L: The MARINA model (Model to Assess River Inputs of Nutrients to seAs): model description and results for China. Science of the Total Environment 2016, 562:869-888.

9 Wang M, Kroeze C, Strokal M, van Vliet MT, Ma L: Global change can make coastal eutrophication control in China more difficult. Earth's Future 2020, 8:1-19.

10 Strokal M, Spanier JE, Kroeze C, Koelmans AA, Flörke M, Franssen W, Hofstra N, Langan S, Tang T, van Vliet MTH, et al.: Global multi-pollutant modelling of water quality: scientific challenges and future directions. Current Opinion in Environmental Sustainability 2019, 36:116-125.

11 Cunha, JR., C Schott, RD van der Weijden, LH Leal, G Zeeman et al., 2020. Calcium phosphate granules recovered from black water treatment: A sustainable substitute for mined phosphorus in soil fertilization. Resources, Conservation and Recycling 158, 104791

12 Harder, R Wielemaker, TA Larsen, G Zeeman, G Öberg, 2019. Recycling nutrients contained in human excreta to agriculture: Pathways, processes, and products. Critical reviews in environmental science and technology 49 (8), 695-743

13 Rodriguez Arredondo, M., Kuntke, P., Jeremiasse, A.W., Sleutels, T.H.J.A., Buisman, C.J.N., Heijne, A. ter, 2015. Bioelectrochemical systems for nitrogen removal and recovery from wastewater. Environmental Science : Water Research & Technology 1 (1): 22 - 33.