ROTHAMSTED
RESEARCH

Rothamsted Research
Harpenden, Herts, AL5 2JQ

Telephone: +44 (0)1582 763133
Web: http://www.rothamsted.ac.uk/

Waqas, M., Hawkesford, M. J. and Geilfus, C-M. 2023. Feeding the world sustainably: efficient nitrogen use. *Trends in Plant Science.* 28 (5), pp. 505-508. https://doi.org/10.1016/j.tplants.2023.02.010

Trends in
Plant Science

CellPress

Special issue: Food security

Spotlight

Feeding the world sustainably: efficient nitrogen use

Muhammad Waqas, [1,3,5]
Malcolm J. Hawkesford, [2,4,*,@]
and
Christoph-Martin Geilfus [1,3,5,*]

Globally, overuse of nitrogen (N) fertilizers in croplands is causing severe environmental pollution. In this context, Gu *et al.* suggest environmentally friendly and cost-effective N management practices and Hamani *et al.* highlight the use of microbial inoculants to improve crop yields, while reducing N-associated environmental pollution and N-fertilizer use.

Excessive use of N-fertilizers and ecological consequences

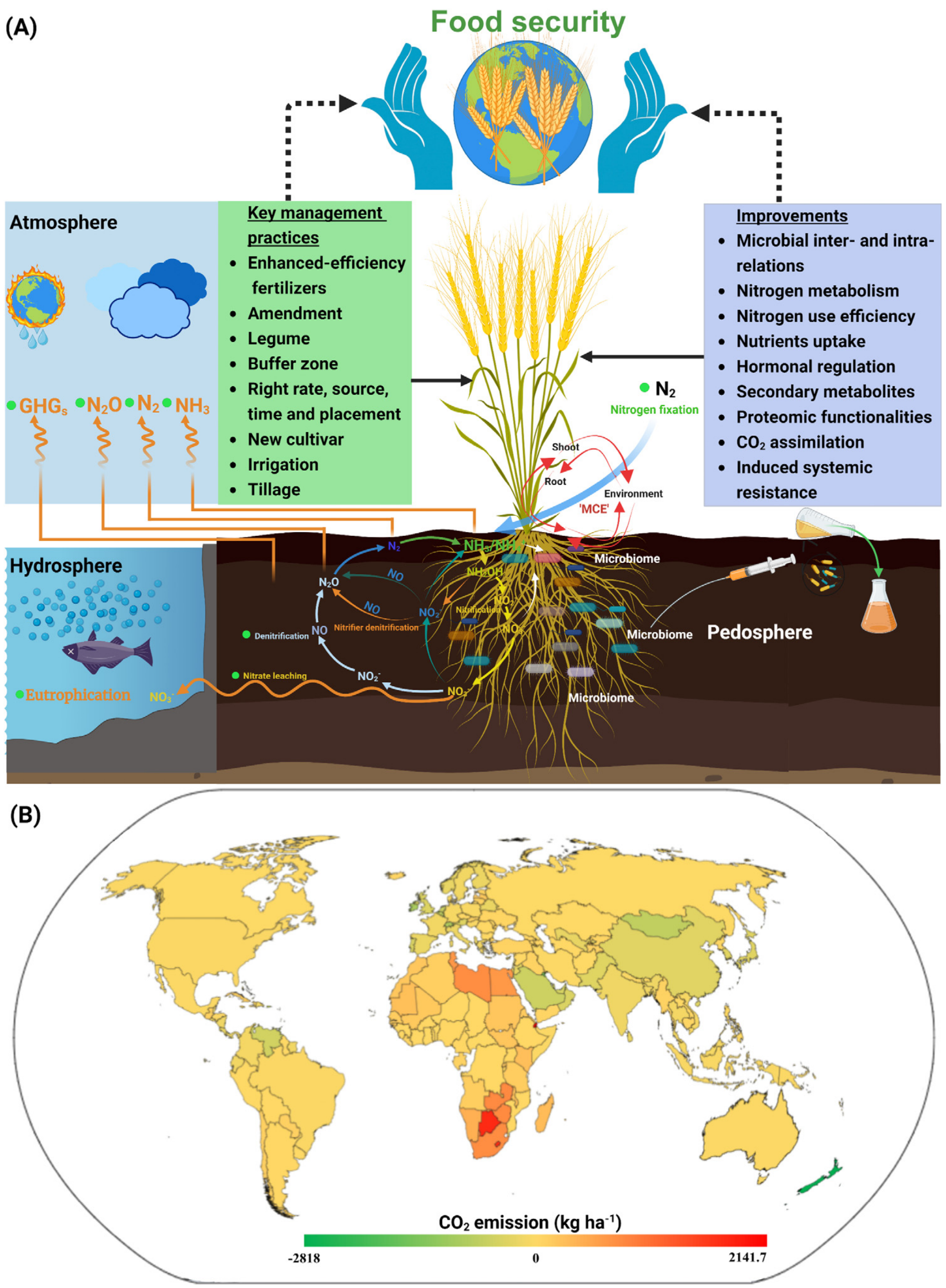
The global population is expected to reach ~10 billion by 2050, necessitating a 50% increase in food production over 2015 levels[i]. The greatest challenge is to feed the growing population with environmental sustainability. Global goals have been set to protect the environment, for example the 'Green Deal' by the European Union, and 'Sustainable Development Goals' by the United Nations. Yet, the misconception of increasing the use of mineral and organic N fertilizers to achieve higher crop yields is widespread around the world. When used excessively, more than 50% of these N inputs are not used by the crop but lost to the environment, causing severe air and water pollution, soil acidification, ozone depletion, biodiversity loss, and climate change [1]. Even ecosystem services are being severely affected by N pollution [2]. To stop ecosystem degradation, an utmost societal need is to maintain environmental N sustainability without compromising crop yields to feed the world.

Nitrogen management by advanced practices

To address this challenge, a global meta-analysis has been conducted by Gu *et al.* [3] utilizing N budget models to examine 1521 field observations published over the past two decades. They identified 11 cost-effective key farm-level management practices for improving crop yields and N use efficiency (NUE) while simultaneously reducing N pollution [3]. These advanced key management practices comprise measures such as enhancing efficiency of N fertilizers by using controlled/slow release- or nitrification/urease inhibitor-fertilizers, organic soil amendments (straw, compost, wood ash, etc.), inclusion of legumes in crop rotations, establishment of **buffer zones** (see Glossary) to prevent N leaching and run-off losses from crop lands to water bodies, which in turn cause **eutrophication**. Also critical is the adoption of the so-called '4R' N fertilizer stewardship: right rate, right source (organic/synthetic and type, such as ammonium/nitrate), right time (split dozes as per crop demand), right placement, (i.e., broadcast, deep placement, band placement, etc). Additionally relevant are use of N-efficient germplasm, appropriate irrigation methods, such as drip irrigation or **fertigation**, and no tillage operations to avoid leaching of nitrate (Figure 1A). These advanced practices were compared using computational modeling with reference to conventional N fertilization used in 2015. As a result, multiple benefits were deduced: among them an environmental N pollution reduction by 32% and crop N uptake improvement by 20%. Lastly, N fertilizers use dropped by 21% globally [3]. Consequently, there is a lower requirement for industrially produced mineral N fertilizer, which is an energy-intensive process with high CO_2 emissions. Translating these savings in N fertilizers estimated by Gu *et al.* [3] into CO_2 equivalents using a conversion factor given elsewhere [4] reveals CO_2 emissions savings of averagely 49.3 kg ha^{-1} per year across the globe (Figure 1B; authors' calculation). However, since the N saved comes not only from mineral fertilizers, but also from manure, these data may be overestimated. For implementation of the new practices, a major challenge is to engage farmers, especially smallholders, who work part-time in non-agricultural sectors [5]. In this vein, effective financial inducements at national, provincial, and local levels are needed to facilitate knowledge diffusion. For this, a so-called 'nitrogen credit system' is recommended, which would facilitate timely adoption of best N measures [3]. It is likely that the most effective strategies or measures crucial for efficient N utilization will be specific at the regional level. For example, regions with high N losses from croplands, such as China, India, and Pakistan, should adopt cost-efficient strategies, including '4R' N fertilizer stewardship,

Glossary

Associative nitrogen fixation: microbes convert atmospheric N_2 to NH_3/NH_4^+ for plants with a loose mutualism association; in turn, roots nourish the microbes with carbohydrates.
Buffer zone: having an area (e.g., tree boundary) between an agroecosystem and an adjacent ecosystem to minimize the passage of substances (e.g., nutrients) to adjacent ecosystems.
Denitrification: microbes perform reduction of NO_2^- and NO_3^- into nitrogenous gases, including NO, N_2O, and N_2.
Eutrophication: enrichment of bodies of water by nutrients, particularly through N leaching and run-off, resulting in disturbance of aquatic ecosystems.
Fertigation: applying nutrients with irrigation water, usually through a drip system.
Nitrification: microbes perform oxidation of NH_3/NH_4^+ into NO_2^- and then NO_3^-.
Synthetic microbial communities: co-culturing of many microbial strains under well-defined conditions with the aim of examining interactions between the strains, environment, and plants.



Trends in Plant Science

Figure 1. Model depicting the use of advanced agricultural practices to reduce nitrogen (N) pollution and improve crop yields. (A) Green circles with labels denote positivity factors by the adaptation of key management practices and microbial inoculation. These include: increment of N fixation, reduction of greenhouse gases (GHGs) emissions, and reduction of N losses in ecospheres (atmo-, hydro-, and pedosphere). The cycle in red (arrows) points to the microbial circular economy (MCE) observed in plant–microbe interactions [7]. For supplying N to the plants, the practice of key management (left green rectangle) and use of microbial inoculation result in improvements of soil health and several physiological elements in plants (right light-blue rectangle). (B) Savings in N fertilizers due to the introduction of the 11 advanced key measures as estimated by Gu *et al.* [3] are translated into CO_2 equivalents. This reveals CO_2 emission savings of an average of 49.3 kg ha^{-1} per year across the globe. (A) created with BioRender (www.biorender.com); (B) created with software R version 4.2.0.

and suitable irrigation techniques to mitigate these losses. This includes using compost and manure to improve soil organic matter, avoiding counterfeit fertilizers and flood irrigation, and following appropriate irrigation rates and schedules.

Nitrogen management by microbial inoculation

Microbial inoculants are recognized as a key element of sustainable agriculture for achieving efficient crop nitrogen management. Hamani *et al.* recently used high nitrogen-fixing strains (*Bacillus brevis*, *Bacillus laterosporus*, and *Saccharomyces*) to inoculate wheat plants in a pot experiment via irrigation on the 21st day after germination. After growing the plants with specific climate conditions [humidity: 40–50%, photoperiod: 12 h with 600 μmol $m^{-2}s^{-1}$ photons, temperature: 30°C (day) and 20°C (night)], the authors found that the inoculants not only reduced synthetic N use, but also improved shoot and root dry matter by 9.4% and 21.3%, respectively, and furthermore reduced global warming potential by ~60% due to reduced N_2O and CO_2 pollution [6].

Some microbes provide N to the plant by **associative nitrogen fixation**. In associative plant–microbe interactions, interaction partners (i.e., microbe and plant) exchange multiple signals, nutrients, and metabolites through the rhizosphere. Plants feed metabolites to microbes via root exudation. In turn, microbes provide the plant with N-containing metabolites to improve productivity. This interkingdom metabolite exchange is very efficient, systematic, and a seemingly waste-free system [7]. However, the availability of N from associative N fixation needs to be strictly orchestrated with other N fertilization practices and crop N demand, because improper N application can result in environmental deterioration by **nitrification** (fostering of NO_3^- leaching), and **denitrification** [8] fostering emission of greenhouse gases (GHGs; Figure 1A). For instance, an inappropriate large dose of N made available by the activity of microbial inoculants may cause high emissions of N and GHG [6]. However, when implemented thoughtfully, the practice of microbial inoculation ensures the availability of N from the atmosphere by fixation to fulfil crop demands.

Although microbial application in the field remains challenging, research efforts over the past few years are facilitating this technology: high-throughput sequencing (i.e., to identify the site-adapted competitive microbes) and use of **synthetic microbial communities** (i.e., to understand interactions among hundreds of strains and the plant) increased survival rates and stability of these bacteria and crop compatibility through positive synergy [9].

Microbial communities are complex and interconnected; selection of individual growth-promoting strains or deletion of pathogenic strains is usually inefficient and laborious. The current development of a computational program, ‘ssCRISPR’, is anticipated to revolutionize microbial research and industry. This program designs strain-specific CRISPR guide RNA sequences, which will facilitate modification of the complex microbial communities [10]. This should enable the selection and cultivation of associative N-fixing strains that survive longer when being introduced in a soil where they are not native.

Concluding remarks and future perspectives

Gu *et al.* [3] identified 11 advanced N management practices to improve crop yield and reduce N pollution cost-effectively at the field level [3]. The authors obtained underlying data in most cases from countries of the Northern Hemisphere. To get a better picture of the efficiency of these practices, more studies are warranted in the Global South and East. The authors also suggested a ‘nitrogen credit system plan’ to subsidize farmers who are willing or have adopted best N measures [3]. Additionally, to aid minimum N fertilizer application for environmental sustainability, Hamani *et al.* highlighted that the use of microbes can save a large amount of fertilizer N. Of note, this enables lower N and GHGs emissions and better crop productivity [6]. In this context, associative N-fixing strains are of interest because they could work efficiently with cereal crops [11]. However, new crop rotations, germplasm, and tillage systems must also be considered in this context. Finally, there is large variability in soil physicochemical properties, at all spatial scales. To estimate local supply of N, user-friendly and economical soil-testing devices should be introduced, which will output crop nutrient demand based on regional soil properties. Reaching a high level of sustainable N management is a thorny road but can be achievable by adopting advanced genetic and agronomic practices, including microbial use, which will need systematic collaboration among academia, industry, and growers. Extension services will serve as key mediators between these groups. Currently, the diffusion of best practice knowledge to rural agricultural participants is a massive problem [12]. Furthermore, the implementation of such measures must also be anchored in, and facilitated by, national laws. Globally, the rapidly growing population and environmental degradation are demanding solutions. Feeding the world with environmental sustainability will include efficient N management.

Acknowledgments

We thank the Deutsche Forschungsgemeinschaft (DFG) (grant number 498546397 to C-M.G.) for supporting the work. M.J.H. was supported by the Biotechnology and Biological Sciences Research Council Designing Future Wheat Programme (BB/P016855/1).

Declaration of interests

No interests are declared.

Resources

[i] www.fao.org/3/i6583e/i6583e.pdf

[1]Department for Plant Nutrition and Soil Science, Hochschule Geisenheim University, 65366 Geisenheim, Germany
[2]Rothamsted Research, West Common, Harpenden, AL5 2JQ, UK
[3]Website: www.hs-geisenheim.de/en/research/departments/soil-science-and-plant-nutrition/department-of-soil-science-and-plant-nutrition/
[4]Website: www.rothamsted.ac.uk/our-people/malcolm-hawkesford
[5]Instagram: www.instagram.com/soilsciplanutri_hgu/?igshid=YmMyMTA2M2Y=

*Correspondence:
malcolm.hawkesford@rothamsted.ac.uk (M.J. Hawkesford) and ChristophMartin.Geilfus@hs-gm.de (C.-M. Geilfus).
@Twitter: @malcolmhawkesf2 (M.J. Hawkesford).

https://doi.org/10.1016/j.tplants.2023.02.010

References

1. Erisman, J.W. *et al.* (2013) Consequences of human modification of the global nitrogen cycle. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 368, 20130116
2. Compton, J.E. *et al.* (2011) Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecol. Lett.* 14, 804–815
3. Gu, B. *et al.* (2023) Cost-effective mitigation of nitrogen pollution from global croplands. *Nature* 613, 77–84
4. Longo, S. *et al.* (2016) Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. *Appl. Energy* 179, 1251–1268
5. Gu, B. *et al.* (2021) A credit system to solve agricultural nitrogen pollution. *Innovation* 2, 100079
6. Hamani, A.K.M. *et al.* (2023) Optimized application of combined nitrogen and microbial decomposing inoculants increases wheat (*Triticum aestivum* L.) physiological growth and mitigates global warming potential under different water regimes. *Environ. Exp. Bot.* 206, 105170
7. Korenblum, E. *et al.* (2022) Plant–microbe interactions in the rhizosphere via a circular metabolic economy. *Plant Cell* 34, 3168–3182
8. Klimasmith, I.M. and Kent, A.D. (2022) Micromanaging the nitrogen cycle in agroecosystems. *Trends Microbiol.* 30, 1045–1055
9. Shayanthan, A. *et al.* (2022) The role of synthetic microbial communities (syncom) in sustainable agriculture. *Front. Agron.* 58, 896307
10. Rottinghaus, A.G. *et al.* (2023) Computational design of CRISPR guide RNAs to enable strain-specific control of microbial consortia. *Proc. Natl. Acad. Sci. U. S. A.* 120, e2213154120
11. Guo, K. *et al.* (2022) Biological nitrogen fixation in cereal crops: progress, strategies and perspectives. *Plant Commun.* 100499
12. Cook, B.R. *et al.* (2021) Humanising agricultural extension: a review. *World Dev.* 140, 105337