SCIENTIFIC PANEL
ON RESPONSIBLE PLANT NUTRITION

A NEW PARADIGM FOR PLANT NUTRITION

Issue Brief, November 2020

KEY POINTS

Nutrient inputs play a critical role in raising crops and livestock for food security, human nutrition and other uses in the bioeconomy. Their production and management must change to more effectively nourish crops, reduce harmful environmental impacts caused by nutrient losses and contribute to restoration of soil health. A new paradigm for plant nutrition follows a food system approach in which multiple socioeconomic, environmental and health objectives must be achieved (Fig. 1).

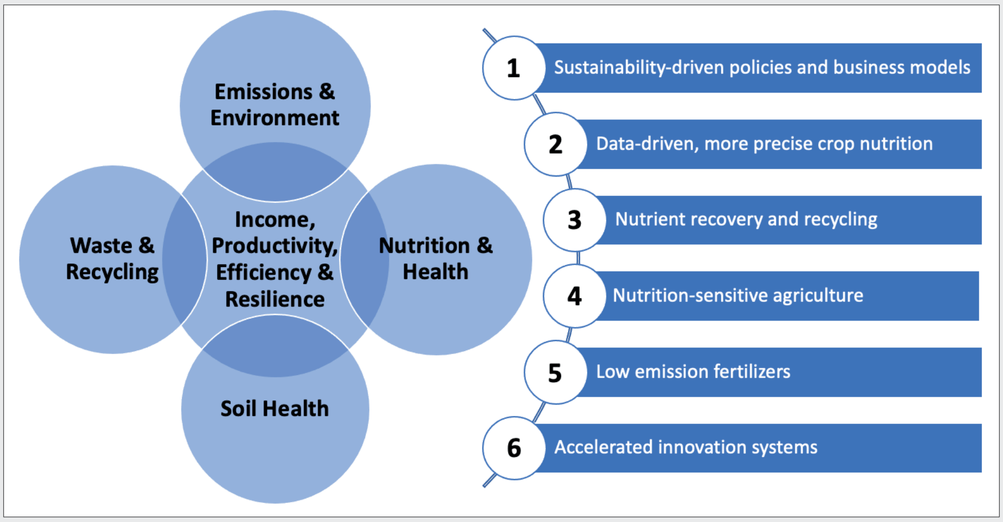


Figure 1. The five interconnected aims of responsible plant nutrition, and six key actions to take.

The coming 10-20 years will be most critical for making the transition to a global food system in which all stakeholders look at food and nutrients in a holistic manner, including their hidden environmental, health and socio-economic costs. Consumers as well as governments and other stakeholders need to support such a transformation because farmers and the industry supporting them will not be able to implement all of the required actions alone.

The outcome of this transformation will be a new societal plant nutrition optimum rather than a purely economic optimum. The new nutrient economy will become an integral component of a low carbon emission, environment-friendly and circular economy, supporting the food and nutrition requirements of a rising global population and improving the income and livelihood of farmers worldwide. Success is described in nine points at the conclusion of this brief.

WHAT IS THE ISSUE?

World agricultural output has grown at an average annual rate of about 2.2% during the past 60 years, although with huge variations among countries ***(1)***. Similar growth will be required in the near future to feed a growing world population and improve rural livelihoods. Over the longer term, slowing population growth, changing diets, reduced food losses and waste, and increased nutrient recycling will ease the pressure to produce more food and utilize more natural resources in that process.

Historically, economic development has been faster in regions of the world where fertilizer use and crop yields rose in parallel ***(2)***. The increasing access to mineral fertilizers has been one of the main ingredients of feeding the rapidly growing world population ***(3)***. Rapid increases in crop yields also prevented a much larger expansion of agriculture into natural lands that would have otherwise occurred ***(4)***. On the other hand, in many regions, intensive farming to support the emerging food consumption patterns has resulted in nutrient-related externalities that are difficult to manage, such as land degradation, biodiversity loss, unsustainable water withdrawal, eutrophication of many freshwater and coastal marine ecosystems, increased greenhouse gas emissions or inequality among farmers ***(5)***.

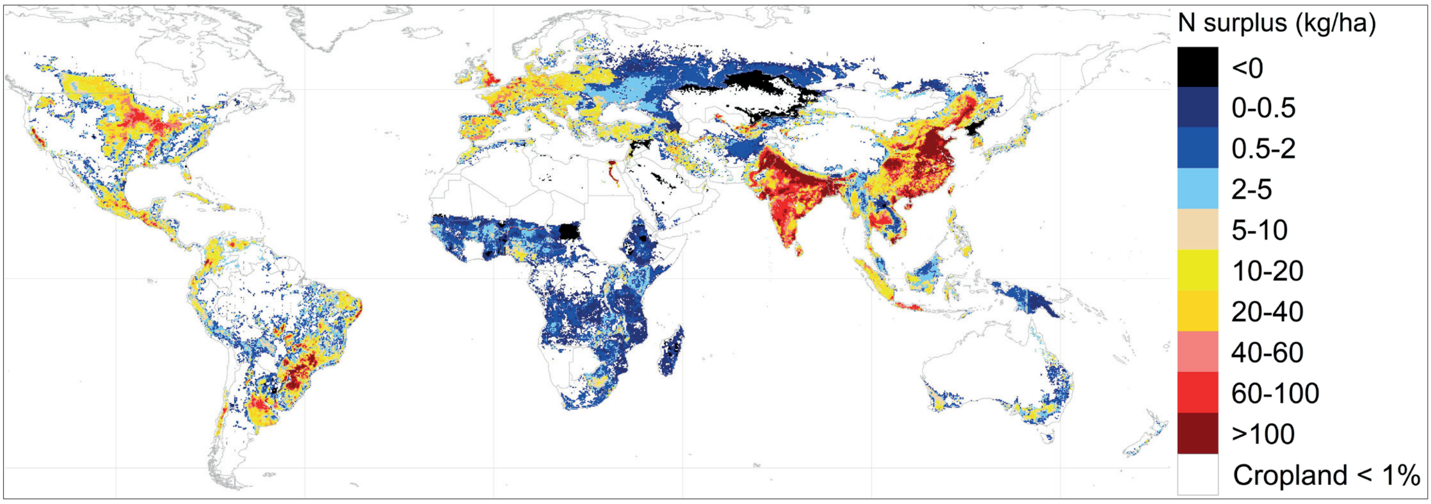
Anthropogenic perturbation levels of global nitrogen and phosphorus flows may already exceed limits that are deemed to be a safe operating space for humanity ***(6)***. While agricultural activities at the farm level account for 9 to 14% of greenhouse gas (GHG) emissions from all human activities, a full accounting for the global food system, including land use change and fertilizer production, raises the figure to 21 to 37% ***(7)***. Human-induced emissions of nitrous oxide (N2O), which are dominated by fertilizer additions to croplands, have increased by 30% since the 1980s ***(8)***. Current food systems also favor the cultivation of staple crops at the expense of more micronutrient-rich food crops. While hunger and malnutrition have significantly declined in recent decades, they have stubbornly persisted in sub-Saharan Africa and other regions, including micronutrient-related deficiencies that particularly affect women and children ***(9)***. The number of people who do not have access to sufficient and nutritious food may continue to rise again due to conflict, climate extremes, economic downturns, or outbreaks of diseases ***(10)***.

It has been estimated that $12 trillion hidden health, environmental and socio-economic costs are associated with the global food system, which is larger than the system's output at current prices ***(11)***. While food security through increasing crop and animal productivity will remain hugely important in light of an expected population of about 9.5 billion by 2050 ***(12)***, it is no longer the only objective. The transition to a more sustainable global food system requires all stakeholders to manage nutrients and their entire life cycle in a more holistic manner. Future plant nutrition solutions will have to address multiple global and regional challenges related to nutrients in the food system.

In that context, ten higher-level questions that need to be resolved within the next 20 years are:

1. **How can we overcome the current global nutrient imbalance?** For many decades, rising crop and livestock production was closely coupled with increasing input of nitrogen and other nutrients, as well as international trade of feed and food. This has led to a global divide, ranging from large nutrient input-output surpluses and environmental pollution in some regions to large nutrient deficits in others (Fig. 2). On a global scale, how can future growth in primary crop production be decoupled from growth in fertilizer consumption? What are the country-specific targets and roadmaps for fertilizer use and nutrient use efficiency that will enable that?

2. **What are the key measures to double or triple crop yields in Africa with increasing and balanced nutrient inputs?** Africa has massive nutrient deficits that must be overcome to increase crop yields and achieve higher levels of food security within one generation ***(13)***. The average fertilizer use in sub-Saharan Africa is about 20 kg nutrients/ha and exceeds 50 kg/ha in only few countries, which is far below what is required to boost crop production and replenish soil fertility after decades of depletion. Fertilizer alone will not be sufficient to lift crop yields, but it is a key ingredient to trigger an African Green Revolution ***(14)***, which must be based on good information, incentives for efficient use of nutrients, and specific measures to also tackle the still persistent forms of malnutrition.



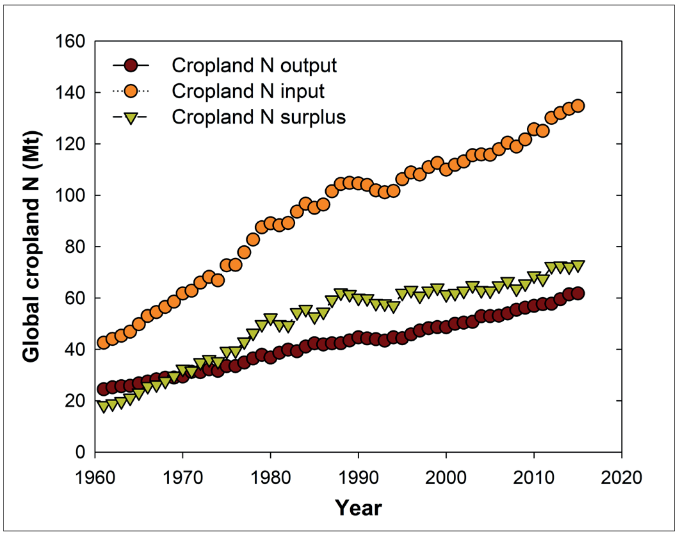


Figure 2. Global trends in crop nitrogen output, input from fertilizer and other sources, and annual nitrogen surplus (left), and map of nitrogen surplus or deficit in 2015 (top, kg N/ha). N surplus is defined as the total N input to cropland minus N harvested as crop products (15); it is expressed as million tons (Mt) in the left panel, and as kg per hectar land area in the top panel, indicating the potential pressure due to N lost from crop production. Source: Xin Zhang and Guolin Yao, University of Maryland Center for Environmental Science.

3. **What data-driven technologies, business solutions and policies will accelerate the adoption of more precise nutrient management solutions by farmers?**
   In many countries, farmers apply too much nutrients because they are relatively cheap or they do not want to risk loss of yield. In other situations, farmers may not apply sufficient nutrients or in the wrong formulations because of lack of affordability, access, knowledge or data. Many good examples exist worldwide for how to overcome this, but only a few have led to breakthroughs at a larger scale.

4. **Can nutrient losses and waste along the whole agri-food chain be halved within one generation?**
   Current estimates suggest that at global scale only around 20% of applied nitrogen compounds may reach useful products, with up to 80% lost to the environment in different forms ***(16)***. There are huge variations in nutrient losses among countries and their food systems which can be addressed through various means, including greater recovery of nutrients from various waste streams in forms that allow safe recycling back to crop production.

5. **How can nutrient cycles in crop and livestock farming be closed?**
   Globally operating demand drivers and supply chains have caused a separation and concentration of crop and livestock farming, resulting in spatially disconnected, leaky nutrient cycles. The massive growth of the livestock sector has led to low nutrient use efficiency, increased waste and large greenhouse gas emissions. Global livestock supply chains account for one-third of all human-induced nitrogen emissions ***(17)***. Sustainable livestock production includes more pasture-based systems and re-integration of crop and livestock farming to utilize animals for what they are good at: converting by-products from the food system and forage resources into valuable food and manure ***(18)***.
   What future farm structures, technologies and supply chains will enable that?

6. **How can we improve soil health?**
   Soils are vital for growing crops, but they also support other essential ecosystem services, such as water purification, carbon sequestration, nutrient cycling and the provision of habitats for biodiversity. Carbon and nutrient inputs are important triggers for improving soil health in crop production, which also increases the resilience of farming systems to extreme climatic events. Sequestration of atmospheric CO_2 in soils can contribute to reducing global warming and improving soil health, but requires continuous organic matter inputs and nutrient inputs (particularly nitrogen and phosphorus) to form stable soil organic matter. How can a holistic plant nutrition approach manage macro- and micro-nutrients for high crop productivity and nutrient use efficiency, but also utilize biological N fixation, optimize carbon storage and turnover, increase soil biodiversity, and avoid soil acidification or other forms of degradation?

7. **How should we manage nutrition of crops in changing climates?**
   Climate change has positive as well as negative impacts on the nutritional quality of crops, many of which are not yet well understood ***(19)***. Rising atmospheric carbon dioxide (CO_2) may increase crop yields but also cause declining nutrient concentrations and nutrient use efficiency of food crops. Global warming will increase the risk of crop stresses such as drought, heat or high radiation, for which balanced plant nutrition plays particular roles in mitigation. Changes in seasonality, precipitation and extreme weather events will also affect the timing and efficiency of nutrient uptake, requiring integration of nutrient advisories with early warning and climate information systems.

8. **What are realistic options and targets for reducing fertilizer-related greenhouse gas emissions?**
   All pathways that limit global warming to 1.5°C or well below 2°C require land-based mitigation and land-use change ***(20)***. Across the plant nutrition sector, low-emission "green" fertilizer production and transportation technologies, novel fertilizer formulations, inhibitors, genetic solutions to nitrification inhibition or fixing atmospheric N, as well as more precise nutrient application and agronomic field management offer numerous opportunities to reduce nutrient-related emissions of CO_2 and N_2O - provided that the surrounding policies and market conditions enable that.

9. **How can cropping systems deliver high quality, more nutritious food?**
   More than 2 billion people in the world are affected by various forms of micronutrient malnutrition. The world's major cropping systems are designed to provide calories, protein and a number of other nutrients or bioactive compounds. A handful of micronutrient-poor crops dominate the global food and feed chains and have often decreased crop diversity or displaced traditional crops such as pulses. What agricultural practices can be deployed to improve human nutrition, including plant nutrition solutions ***(21)***?

10. **How can we better monitor nutrients and implement high levels of sustainability stewardship?**
   Digital technologies offer great potential for better monitoring, analysis, benchmarking, reporting and certification of sustainability efforts across the entire nutrient chain. This would improve transparency, traceability, quality control, and sustainability assessment in the whole food sector, and it is also critical for public sector engagement and evidence-based policy making. How, for example, can the International Code of Conduct for the Sustainable Use and Management of Fertilizers ***(22)*** or criteria for Environmental, Social, and Governance (ESG) be implemented by countries and industry? Is there a need for a new standard on sustainable production and use of nutrients?

WHAT CAN BE DONE?

Human development, biological process requirements and mass balance principles make it clear that mineral nutrients, including fertilizers, will continue to be major ingredients of future food systems. It is critical to develop integrated and targeted plant nutrition strategies and practices that minimize tradeoffs between productivity and the environment - and are viable in the farming and business systems of different regions, nations and localities. Integration in this context has several dimensions, including a multi-nutrient food system approach, greater recycling and utilization of all available nutrient sources, alignment with other agronomic and stewardship practices, and compliance with high sustainability standards.

The new paradigm of responsible plant nutrition encompasses a broad array of scientific and engineering know-how, technologies, agronomic practices, business models and policies that directly or indirectly affect the production and utilization of mineral nutrients in agri-food systems. Following a food system approach, respon–sible plant nutrition aims to:

A. Improve income, productivity, nutrient efficiency and resilience of farmers and businesses supporting them
B. Increase nutrient recovery and recycling from waste and other under-utilized resources
C. Lift and sustain soil health
D. Enhance human nutrition and health through nutrition-sensitive agriculture
E. Minimize greenhouse gas emissions, nutrient pollution and biodiversity loss

In a nutshell, responsible plant nutrition will contribute to a more nature-positive approach of food production and consumption. It does not aim to blindly copy nature, but, following science, it also adapts and integrates key agroecological principles *(23)* in a tailored manner. Implementing the new paradigm involves six interdependent actions:

Action 1: Sustainability-driven nutrient policies, roadmaps, business models and investments that create added value for all actors and beneficiaries in the nutrient chain. Nutrient policies and roadmaps must be tailored to the specific food systems in every country, including ambitious goals for nutrient use, losses and efficiency. Specific targets and priorities for managing nutrients will vary, depending on each country's history and sustainable development priorities. Progressive science-based monitoring, stewardship *(24)* and certification schemes will guide performance and reward farmers and businesses for innovation, reduction of nutrient losses, improvement of soil health, enhancement of biodiversity and provision of other ecosystem services. Differentiated strategies will also lead to regional shifts in global fertilizer use, reducing nutrient surpluses and ensuring that more nutrients are moved to where they are most lacking, particularly in many parts of Africa *(25)*.

Action 2: Data-driven, more precise crop nutrition solutions. Knowledge-driven digital solutions and disruptive technologies will allow tailoring nutrient applications to local needs in an increasingly precise manner. Besides high-tech solutions for commercial farming, "low-tech" site-specific nutrient management approaches have shown consistent, large increases in crop yields and profits and nutrient use efficiency in many crops grown by smallholder farmers in Asia and Africa *(26, 27)*. They now need to be upscaled to millions of farmers through digitally supported advisory systems and business solutions.

Action 3: Circular economy solutions for greater nutrient recovery and recycling. Crop-livestock integration, less food waste, by-products use and increased nutrient recovery and recycling are key measures to optimize nutrient use efficiency across the full food chain (Fig. 3). Political incentives, novel technologies and shifts in behavior will drive greater nutrient recycling from multiple waste streams, as a key contribution to circular, bio-based economies. Such circular systems need to be safe and healthy for animals, humans and the environment, but they also allow the creation of novel business models, including side-streams within the agricultural sector for up-cycling of materials and the nutrients they contain. Improved full-chain nutrient flow monitoring, life-cycle analysis, benchmarking and certification will support the development of such solutions.

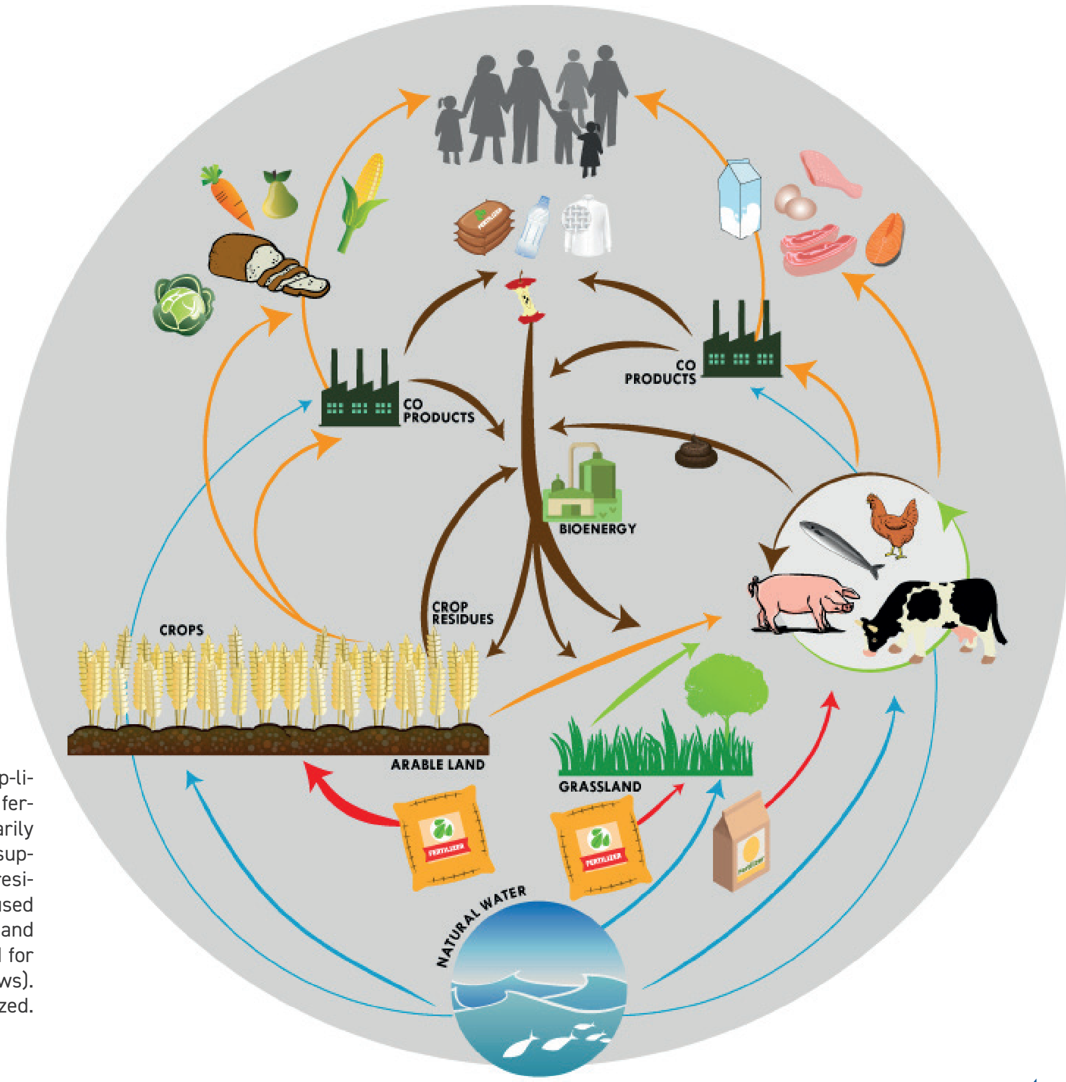


Figure 3. Major nutrient flows in circular crop-livestock-human systems. Red arrows indicate fertilizer inputs into the system. Crop land is primarily used to produce food for humans and some supplementary feed for livestock, also from crop residues (orange arrows). Grassland is primarily used for livestock, including grazing. By-products and waste are recycled back to agriculture or used for making new bio-based products (brown arrows). Leakages out of the circular system are minimized. Source: Re-drawn and modified from (18).

Action 4: Nutrition-sensitive farming – producing food crops with higher nutritional value to address persisting as well as emerging mineral nutrient deficiencies. Besides dietary diversification and food interventions, plant nutrition solutions are part of strategies for addressing the triple burden of undernutrition, micronutrient malnutrition, overweight/obesity and other non-communicable diseases. Depending on the local context, nutrition-sensitive crop production may include more diverse crop rotations as well as biofortification of staple crops with micronutrients through breeding and/or fertilizers ***(28).*** The latter involves the targeted use of fertilizer products that deliver micronutrients of importance to crops, animals and humans. Besides essential plant nutrients such as iron or zinc, this may also include nutrients that are of particular importance to animals and humans, such as iodine (29) or selenium ***(30).***

Action 5: Energy efficient, low emission fertilizers. Fertilizers will increasingly be produced in an environmentally friendly manner and they will embody greater amounts of knowledge to control the release of nutrients to the plant. Significant reductions in pre-farm greenhouse gas emissions can be achieved by low-carbon emission fertilizer production. Various new technologies are already being piloted to produce "green ammonia" from renewable, carbon-neutral energy sources, and also use it for energy storage and transport. A new "ammonia economy" could feed and power the world in a whole new, decentralized manner ***(31).*** Innovation in fertilizer formulation will lead to environmentally-friendly fertilizers that maximize nutrient capture by the crop and minimize losses of nutrients ***(32).***

Action 6: Accelerated, more open innovation systems for faster translation of new ideas into practice. Future research and innovation systems need to foster co-creation and sharing of knowledge for rapid development and deployment of new know-how and technologies. This requires more openness and coordinated action of public and private sector players. A massive culture change is needed in science and science funding, towards a problem-focused and leaner science approach, transdisciplinary collaboration, entrepreneurship, and early engagement with users - including the full diversity of farmers.

WHAT CAN BE DONE?

Responsible plant nutrition is a complex and global challenge which can only be tackled through concrete action by all those directly involved in the nutrient cycle, and those influencing it (Fig. 4).

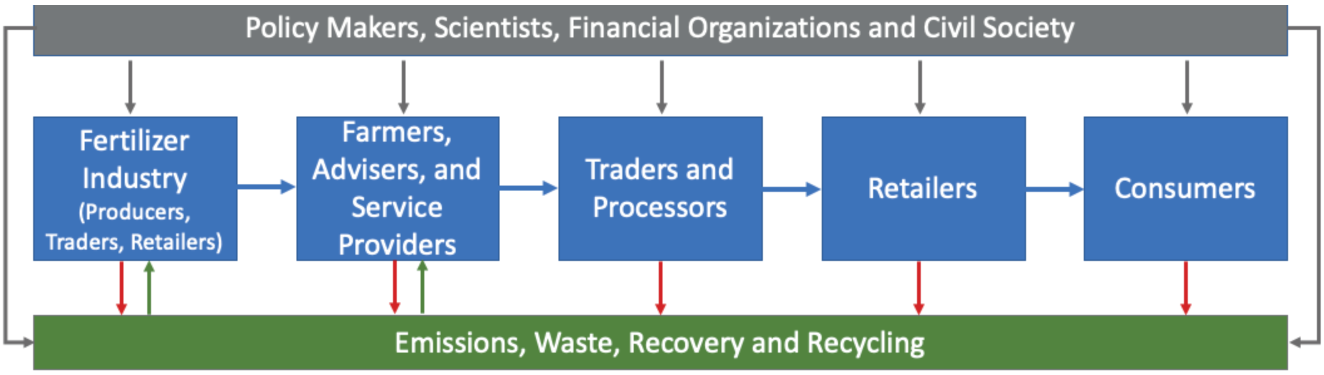


Figure 4. The agri-food chain from a nutrient management perspective. Blue boxes show actors who directly contribute to nutrient use and losses at different stages. Red arrows indicate greenhouse gas emissions, nutrient losses into the environment and waste that can happen in all parts of the chain. All opportunities to reduce emissions and losses must be exploited, while also increasing nutrient recovery and return to farming and industry (green arrows). The grey box shows actors who influence the major actors, drive innovation or set the societal framework for action. Source: Modified from ***(33).***

Policy makers at all levels need to create clear, science-based and harmonized regulatory frameworks for nutrients, but also dynamic policies that incentivize innovation in technologies, practices and business models. They must set out a clear vision for national or regional roadmaps with sound targets for nutrients, nutrition and environmental indicators. They can drive changes in food consumption, as well as provide progressive incentives for the adoption of better practices by farmers. Policies need to properly balance food production and environmental goals. Technical assistance and extension services must be supported adequately to promote sustainable practices. Policy makers also need to ensure that farmers all over the world have affordable access to the internet and digital services.

The global fertilizer industry has recently recognized the need for a sustainability- and innovation-driven plant nutrition approach as its core business strategy ***(34).*** Fertilizer companies will have to increasingly become providers of integrated plant nutrition solutions that are based on new business models that do what is right for people and the planet. Sustainability and innovation, including transparent monitoring and reporting, will drive the transformation strategy for the entire industry, for every product and solution sold. Revenue growth primarily needs to be driven by growth in performance value offered to farmers and society, not volume of fertilizers sold.

Farmers, farm advisers and service providers carry the primary responsibility for improving nutrient use efficiency, reducing nutrient losses, recycling nutrients and promoting soil health at the farm scale, which has huge implications at larger scales. They need to be able to fully adapt and adopt new knowledge, technology, and services, and they need to be rewarded for good practices. Many farmers are entrepreneurs and willing to change, and they are also aware of their role as stewards of land, water, climate and biodiversity. But doing things differently requires lowering risks and other adoption barriers.

Food traders, processors and retailers have enormous power to influence nutrient cycles, both through influencing what consumers eat or drink and how it is being produced. Vertically integrated, data-driven and more transparent supply chains that meet sustainable production standards and reduce production losses will become more widespread, including more direct sourcing from farmers. These developments offer numerous opportunities for implementing more holistic approaches to nutrient management. Monetizing such sustainable production practices is both a key challenge and an opportunity.

Consumers will drive significant changes in plant nutrition through changes towards healthier diets as well as an increasing emphasis on food that is produced in a more sustainable manner. Specific trends will differ among regions and income groups. On a global scale, changes in food behavior may be relatively slow and will also be partly compensated by growing food consumption due to rising populations and income growth in low and middle income countries. However, an immediate responsibility of consumers is to reduce excessive meat consumption, waste less food and ensure recycling of waste that does occur.

Utility services providers and waste processors are an important and relatively new category of actors in the nutrient cycle, but their role will increase substantially in the coming years. Particularly in densely populated areas their needs and actions will increasingly co-define how farming and nutrient management will be done. This requires deepening the collaboration with other groups of actors and jointly developing a common understanding as well as common standards to meet.

Investors: Investment in plant nutrition research and innovation will need to increase massively to meet the complex plant nutrition challenges we face. Public, private and philanthropic investors should increasingly invest in technologies, businesses and organizations that support key elements of the new paradigm, including creating a growing ecosystem of startup companies and other enterprises. Use of blended public and private capital can de-risk and leverage more private investment.

Scientists: Science and engineering will underpin all efforts to achieve the multiple objectives of the new plant nutrition paradigm, but the entire science culture must change too, towards new ways of working that stimulate new discoveries and achieve faster translation into practice. Greater focus on explicit pathways to agronomic applications, reality checks and rigor in claims of utility are needed, as well as more sharing of know-how and critical resources, more open innovation and entrepreneurship.

Civil society organizations play significant roles for the new paradigm through informing the public, grassroots mobilization, monitoring, alerting and influencing, and inclusive dissemination of new technologies and practices. This is a big responsibility, which should follow an evidence-based approach. Co-developing concrete solutions in partnership with government, industry, science and farmers should replace the often found emphasis on single issues or controversial debates.

WHAT WILL SUCCESS LOOK LIKE?

Compared to where we are in 2020, concrete outcomes that can be achieved within one generation, by 2040, include:

1. Widely accepted standards for quantifying and monitoring nutrients along the food supply chain inspire solutions for improving overall nutrient use efficiency, increasing recycling and reducing nutrient waste across the whole agri-food system. Ambitious targets, policies and investments stimulate collective actions by governments, businesses, farmers and other stakeholders towards sustainable, integrated, and tailored plant nutrition solutions.

2. On a global scale, crop yield growth meets food, feed and bio-industry demand and outpaces growth in mineral fertilizer consumption, while cropland expansion and deforestation have been halted. Global crop nitrogen use efficiency – the nitrogen output in products harvested from cropland as a proportion of nitrogen input – has increased to 70%.

3. Through responsible consumption, increased recycling, and better management practices nutrient waste along the food system has been halved. Nitrogen and phosphorus surpluses in hotspots have been reduced to safe levels which minimize eutrophication and other environmental harm.

4. Soil nutrient depletion and carbon loss have been halted. Forward-looking policies and investments have triggered changes in farming systems and management practices that increase soil health, including soil organic matter. Regional soil nutrient deficits have been reduced substantially, particularly in sub-Saharan Africa, where fertilizer use has tripled and crop yield has at least doubled, including improved nutritional outputs. Millions of hectares of degraded agricultural land have been restored, including through the use of mineral and organic fertilizers and nutrient-containing waste or by-products.

5. Extreme forms of chronic hunger and nutrient-related malnutrition have been eradicated through integrated strategies that include the targeted use of micronutrient-enriched fertilizers and nutrient-biofortified crops. A new generation of more nutritious cereals and other staple crops is increasingly grown by farmers, driven by consumer and market demand. Policy and decision makers support mineral fertilization strategies for meeting specific human nutritional needs where markets do not provide the needed incentives.

6. The fertilizer industry follows rigorous and transparent sustainability standards for the entire life cycle of its products and business operations. Greenhouse gas emissions from fertilizer production and use have been reduced by at least 30% through increased energy efficiency, carbon capture and storage and other novel technologies and products. At least 10% of the world's fertilizer-N is produced from green ammonia with very low or zero carbon emission.

7. R&D investments in plant nutrition research and innovation by public and private sector have tripled compared to present levels. Many companies spend 5% or more of their gross revenue on research and innovation. Collaborative, open innovation approaches allow for scientific discoveries to become quickly translated into practical solutions and knowledge. Innovative, value-oriented business models drive growth throughout the industry.

8. Consumers appreciate the benefits of plant nutrients, including mineral fertilizers as a primary nutrient source. A nutrient footprint standard with high visual recognition informs consumer choices. Information on improvement of soil health and nutrient balances is widely available, and their linkage to the mitigation of air, water and climate issues will be broadly acknowledged.

9. Farmers all over the world have access to affordable, diverse and appropriate plant nutrition solutions, and they are being rewarded for implementing better nutrient management and stewardship practices that increase their prosperity and enable them to exit poverty traps. Customized crop nutrition products and solutions account for at least 30% of the global crop nutrition market value.

So far we have failed to achieve the goals stated above, despite many scientific and technical solutions that have existed for decades. Achieving it now, within one generation, will require a far more concerted effort by everyone involved, from the fertilizer industry to farmers and consumers of food and other agricultural products. Fast action - grounded in long-term sustainability thinking - is need to facilitate the transition towards a new paradigm for plant nutrition.

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