Global Food Security 33 (2022) 100636

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Responsible plant nutrition: A new paradigm to support food system transformation

Achim Dobermann [a,*], Tom Bruulsema [b], Ismail Cakmak [c], Bruno Gerard [d], Kaushik Majumdar [e], Michael McLaughlin [f], Pytrik Reidsma [g], Bernard Vanlauwe [h], Lini Wollenberg [i], Fusuo Zhang [j], Xin Zhang [k]

[a] International Fertilizer Association (IFA), Paris, France
[b] Plant Nutrition Canada, Ottawa, Ontario, Canada
[c] Sabanci University, Istanbul, Turkey
[d] Mohamed VI Polytechnic University (UM6P), Benguérir, Morocco
[e] African Plant Nutrition Institute (APNI), Benguérir, Morocco
[f] School of Agriculture Food and Wine, University of Adelaide, Adelaide, Australia
[g] Plant Production Systems, Wageningen University & Research, the Netherlands
[h] International Institute of Tropical Agriculture (IITA), Nairobi, Kenya
[i] CGIAR Climate Change, Agriculture & Food Security Program, Burlington, VT, USA
[j] Center for Resources, Environment and Food Security, China Agricultural University, Beijing, China
[k] University of Maryland Center for Environmental Science, Frostburg, MD, USA

ARTICLE INFO

Keywords:
Plant nutrition
Nutrients
Nutrient use efficiency
Fertilizer
Sustainable intensification
Circular economy

ABSTRACT

The coming 10–20 years will be most critical for making the transition to a global food system in which mineral nutrients in agriculture must be managed in a more holistic manner. Fertilizers play a particular role in that because they are among the key drivers for securing global food security and improving human nutrition through increased crop yields and nutritional quality. A new paradigm for responsible plant nutrition follows a food systems and circular economy approach to achieve multiple socioeconomic, environmental and health objectives. Achieving that requires utilizing all available organic and inorganic nutrient sources with high efficiency, tailored to the specific features of food systems and agroecosystems in different world regions. Critical actions include: (i) sustainability-driven nutrient roadmaps, (ii) digital crop nutrition solutions, (iii) nutritious crops, (iv) nutrient recovery and recycling, (v) climate-smart fertilizers, and (vi) accelerated innovation. The outcome of this transformation will be a new societal plant nutrition optimum rather than a purely economic optimum. New partnerships and sustainability-focused business models will create added value for all actors in the nutrient chain and benefit farmers as well as consumers. Research needs to become more problem-driven and merge excellent science with entrepreneurial innovation approaches in order to develop robust solutions faster and at larger scale. Evidence-based policies should focus on creating and supporting the necessary nutrient stewardship roadmaps, including realistic national targets, progressive regulation and incentives that support technology and business innovation.

1. The complex role of crop nutrients in feeding the world sustainably

Historically, economic development has been faster in world regions where fertilizer use and crop yields rose in parallel (McArthur and McCord, 2017). World agricultural output has grown at an average annual rate of about 2.2% during the past 60 years (Fuglie, 2018). Along with that, nutrient land productivity has increased by 2.7–2.9% per year for calories and proteins, and between 2.1 and 4.6% for fats, although with huge variation across the world (Tuninetti et al., 2020). Agricultural production growth has relied on both cropland expansion and intensification, with both also driving a massive rise in global fertilizer

Abbreviations: GHG, greenhouse gas emissions; NuUE, nutrient use efficiency; NUE, nitrogen use efficiency; SDG, Sustainable Development Goal.

* Corresponding author. International Fertilizer Association (IFA), 49 avenue d'Iena, 75116 Paris, France.
E-mail address: adobermann@fertilizer.org (A. Dobermann).

https://doi.org/10.1016/j.gfs.2022.100636
Received 22 December 2021; Received in revised form 28 March 2022; Accepted 30 March 2022
Available online 10 April 2022

consumption. During the Green Revolution, except for much of the African continent, the prevailing mode of agricultural production growth has been through increasing yields and efficiency of inputs (Fuglie, 2018), but including periods of regional land expansion in response to food security concerns or global market opportunities. A major concern is that for all of the world's most important crops – rice, wheat, maize and soybean – the relative contribution of cropland expansion to total production increase was larger during 2002–2014 than during the 1980–2002 period (Cassman and Grassini, 2020). Just in the past two decades, global cropland area has increased by another 63 million ha, whereas forest land declined by 94 million ha (FAO, 2021).

However, significant intensification and expansion of agricultural production both had wide-ranging social, economic and environmental impacts. On one hand, higher crop yields and more productive animals have saved billions of people from starvation and millions of hectares of natural ecosystems from being converted to agriculture since the 1960s (Pingali, 2012; Stevenson et al., 2013). On the other hand, intensive animal and crop production to support the emerging food consumption patterns have caused externalities that are difficult to manage. Of great concern are losses of reactive forms of nitrogen (N) and phosphorus (P) into the environment, impacting water quality, biodiversity, air quality and greenhouse gas (GHG) emissions. It has been suggested that anthropogenic perturbation levels of global N and P flows may already exceed limits that are deemed to be a safe operating space for humanity (Steffen et al., 2015), although the validity of such "Planetary Boundaries" remains under debate (Biermann and Kim, 2020). Furthermore, while hunger and malnutrition have significantly declined in recent decades, they have stubbornly persisted in sub-Saharan Africa (SSA) and other regions (Pingali et al., 2017), including micronutrient-related deficiencies that particularly affect women and children.

Food security through increased crop yields will remain hugely important in light of an expected population of about 9.5 billion by 2050 (Vollset et al., 2020), but future yield increases should go hand-in-hand with improvements in environmental and socio-economic outcomes. The coming 10–20 years will be critical for making the transition to a global food system in which we produce and consume food in a more sustainable manner (Willett et al., 2019; Herrero et al., 2020), mitigating much of the estimated $12 trillion hidden health, environmental and socio-economic costs of it (FOLU, 2019). Over 20 different mineral elements are known to be critical for plant, animal and/or human health (Zoroddu et al., 2019; Brown et al., 2021) and many of them enter the food system through crops and grasslands, i.e. from soil, fertilizers, organic manures, biological N fixation and few other sources. Hence, plant nutrients are at the core of the food system transformation because they drive both primary food production and many of the externalities caused by it.

Here we present a new paradigm for managing plant nutrients throughout their life cycle, but we also point out that the priorities and specific solutions for that will vary widely. We present this new paradigm mainly from the perspective of the fertilizer industry and the new roles it should play in the food system, recognizing, however, that many other stakeholders have to make big changes as well.

2. Tough challenges for future plant nutrition

Future plant nutrition solutions will have to address multiple global and regional challenges related to nutrients in the food system. In that context, below we discuss ten higher-level, interconnected questions that need to be tackled with urgency.

(1) How can future growth in primary crop production be decoupled from growth in fertilizer consumption? How can we overcome the current global nutrient imbalance?

For many decades, rising crop production was closely coupled with increasing input of N and other nutrients, mostly from fertilizer. Although estimates vary widely, the global N surplus on cropland – calculated as N inputs from fertilizer, manure, biological N fixation and other sources minus N removed with harvested products – has increased from less than 20 million t N yr^{-1} in 1961 to roughly 90 million t N yr^{-1} in 2010 (Zhang et al., 2021b). Of even greater concern is the global divide, ranging from large nutrient surpluses in some regions to nutrient deficits in others (Fig. 1).

When interpreting Fig. 1 it should be noted that environmental pollution only starts to increase when the N surplus is well above zero (McLellan et al., 2018; Quemada et al., 2020). Likewise, a small N surplus or a neutral N balance may already indicate the presence of soil N mining over time, which is also not desirable. In recent decades, regional differences have become further aggravated by transnational nutrient transfers associated with global trade of feed and food (Grote et al., 2005; Parviainen and Helenius, 2020). Many high-income countries thus outsource a significant amount of the pressure on natural resources to lower-income countries (Sun et al., 2020), but they also have to face the consequences of nutrient excess caused by imports of nutrients.

On a global scale, future growth in primary crop production needs to be decoupled from growth in fertilizer consumption, while also accounting for the huge differences among regions and countries in terms of historical levels of fertilizer use and future needs. Hence, national nutrient roadmaps and solutions for improving nutrient use efficiency (NuUE) will require defining specific NuUE targets for the key agricultural sub-sectors, and carefully crafted regulatory and supporting policies that also take into account the needs of farmers and the agro-food industry as a whole. Encouraging progress has been made in increasing NuUE in regions such as North America, Western and Central Europe in the past 30 years, and more recently also in China (Zhang et al., 2015). What further improvements are feasible and realistic in different parts of the world? What would be the best possible nutrient use efficiencies that ensure high crop yields and avoid excessive surpluses as well as long-term depletion of soil nutrient stocks over time? How can this be implemented across the world, including regions in which subsistence farming remains dominant?

(2) What are the key measures to double or triple crop yields in Africa with increasing and balanced nutrient inputs?

Crop yields in most African countries have risen very slowly, causing the land area under cultivation to more than double in size, whereas agricultural growth in Asia has been largely driven by yield increases on existing land (Fig. 2).

Africa has massive nutrient deficits that must be overcome to increase crop yields and achieve higher levels of food security within the next few decades (van Ittersum et al., 2016; Berge et al., 2019). Annual average nutrient balances in sub-Saharan Africa were estimated to be about −26 kg N ha^{-1}, -3 kg P ha^{-1}, and -19 kg K ha^{-1} in 2000 (Stoorvogel et al., 1993). Although fertilizer use has increased somewhat since then, crop yields have increased somewhat too. Hence, in most countries, net nutrient input-output balances have not improved at all. In reality, there are widespread and unsustainable levels of soil nutrient depletion in most of sub-Saharan Africa, which has been known for a long time. .

In 2006, at a historic Africa Fertilizer Summit in Abuja, Nigeria, heads of state and government declared that "Given the strategic importance of fertilizer in achieving the African Green Revolution to end hunger, the African Union Member States resolve to increase the level of use of fertilizer from the current average of 8 kg per hectare to an average of at least 50 kg per hectare by 2015". However, excluding South Africa, average fertilizer use in sub-Saharan Africa in 2019 was only about 15 kg N + P_2O_5+K_2O ha^{-1} (Source: IFASTAT). Only two countries have achieved the 50 kg ha^{-1} target (Kenya and Botswana), whereas six have at least moved to the 30–50 kg ha^{-1} range (Ethiopia, Zimbabwe, Zambia, Malawi, Benin and Mali), or have much higher fertilizer rates in specific crops already, such as maize in Ethiopia

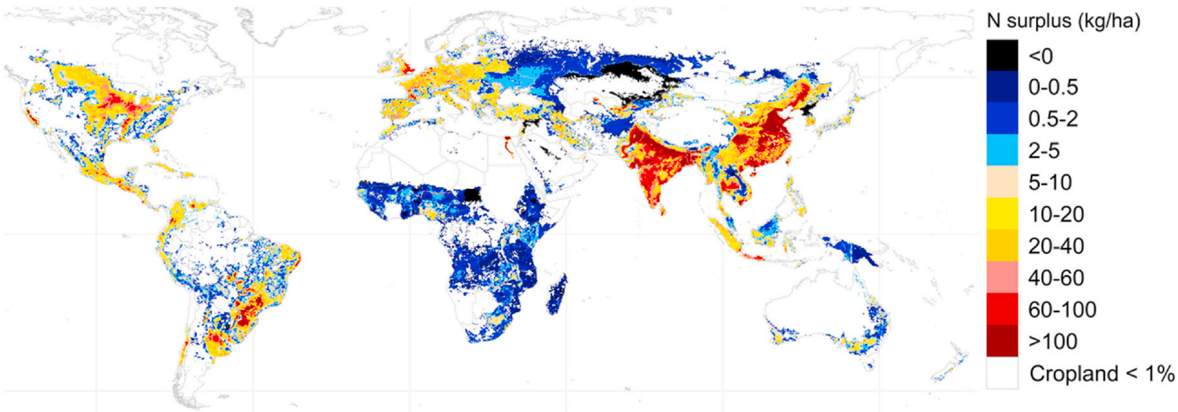

Fig. 1. Global cropland nitrogen surplus or deficit in 2015. Source: Xin Zhang and Guolin Yao, University of Maryland Center for Environmental Science; updated from previous estimates.

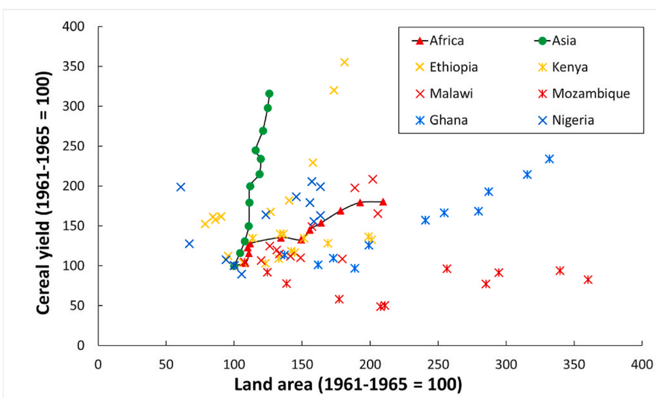

Fig. 2. Relative changes in grain yield and land area used for growing cereals (rice, wheat, maize, barley, sorghum, millet) in Asia and Africa, and in selected countries of sub-Saharan Africa. Data shown are 5-year averages for 1961–2015 and a 3-year average for the period 2016–2018. The average of 1961–1965 was set as 100. Source: FAOSTAT (https://www.fao.org/faostat/).

(Assefa et al., 2021). Fertilizer alone will not be sufficient to lift crop yields, but it is the key ingredient to trigger a uniquely African Green Revolution in areas that are favorable for intensification (Vanlauwe and Dobermann, 2020). This must be based on good information, incentives for efficient use of nutrients to avoid environmental harm, and specific measures to tackle the still persistent forms of malnutrition.

(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 fertilizers because they are affordable and they do not want to risk losses of yield. In other situations, farmers may not apply sufficient nutrients or apply them in the wrong ways because of lack of access, affordability, or information and knowledge. Many good examples exist worldwide for how to overcome this through more precise management of nutrients (Chen et al., 2014; Chivenge et al., 2021), but only few have found wider adoption, even in high-income countries with sophisticated policies and technologies (Silva et al., 2021; Cassman and Dobermann, 2022). Understanding and overcoming that will be of particular importance for increasing nitrogen use efficiency (NUE) in crop production from currently about 50% to at least 70% within the next two decades, a level that is entire feasible if many of the available, known measures could be implemented widely (Hutchings et al., 2020). The potential benefits could be large. A recent analysis for China suggests that the simultaneous implementation of just four measures - improved farm management practices with nitrogen use reductions; machine deep placement of fertilizer; enhanced-efficiency fertilizer use; and improved manure management – would increase crop yields and NUE, reduce N losses to water and massively improve air quality (Guo et al., 2020). Total benefits of US$30 billion per year would exceed the estimated US$18 billion per year in costs.

(4) Can nutrient losses and waste along the whole agri-food chain be halved?

Although accurate data are not available, estimates suggest that at global scale only around 16–20% of nitrogen compounds entering the food system may reach useful products, with up to 80% lost to the environment in different forms (Sutton et al., 2012; Zhang et al., 2020). However, there are huge variations in full-chain NUE among countries, and such estimates also do not account for N that contributes to net increases in soil organic matter, which may also be a desirable outcome with regard to soil health and GHG mitigation. In Europe, due to structural differences of the agricultural sector, full-chain NUE ranges from 10% in Ireland to 40% in Italy (Erisman et al., 2018). Global supply chains are needed to ensure adequate and stable food supply, but potential also exists for more local food production and reduced food movement (Kinnunen et al., 2020). Whether that would also reduce nutrient losses and GHG emissions is not yet fully clear.

Reducing food waste and shifting to healthier diets would positively impact NuUE, nutrient losses and fertilizer requirements in national food systems, but the best outcomes can be achieved in combination with other measures that enhance crop and animal productivity (Ma et al., 2019). Besides, transitions to more plant-based diets may also create additional wastewater P burdens and treatment requirements (Forber et al., 2020). New technologies will likely increase the recovery of nutrients from different organic wastes in the food system in forms that allow safe recycling back to crop production, thus enabling a more circular nutrient economy. What levels of reductions in full-chain nutrient losses and increases in nutrient recovery and recycling can realistically be achieved and at what cost?

(5) How can nutrient cycles in crop and livestock farming be closed?

About 25 billion poultry birds, 2.2 billion sheep and goats, 1.7 billion cattle and buffaloes, and 1 billion pigs are now raised and consumed by humans. In many countries, globally operating production and consumption drivers and supply chains (Sun et al., 2020) 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 NuUE in the whole food chain, increased waste and large GHG emissions (Erisman et al., 2018; Uwizeye et al., 2020). Farmed animals consume more than one-third of the world's cereal grain, as well as about a quarter of all pulses and starchy roots and tubers grown. Global livestock supply chains currently emit 65 Tg N yr^{-1} to air and water in the form of NO_3 (29 Tg N yr^{-1}), NH_3 (26 Tg N yr^{-1}), NO_x (8 Tg N yr^{-1}) and N_2O (2 Tg N yr^{-1}), which is equivalent to one-third of the human-induced N emissions (Uwizeye et al., 2020).

Sustainable livestock production involves many steps (Eisler et al., 2014), including more pasture-based systems and re-integration of crop and livestock farming. If used for what they are good at - converting by-products from the food system and forage resources into valuable food and manure - farm animals can play a huge role in future, more circular farming and food systems (van Zanten et al., 2019). Moreover, optimized micronutrient strategies are required for pasture-based livestock systems because inadequate micronutrients in soils and pasture can affect micronutrient absorption and hence animal health and production, while animal excreta can also be the major input of micronutrients to pasture (Kao et al., 2020). Besides healthier diets with reduced meat consumption, recoupling livestock and cropping systems offers a major path to sustainable agriculture (Herrero et al., 2010), but mixed crop–livestock systems often require higher capital to establish and are also more difficult to manage (Thornton and Herrero, 2015). What future farm structures, technologies and supply chains will enable a better crop-livestock integration?

(6) How can we sustain and improve soil health?

Soils are a growing medium for crops, but they also support other essential ecosystem services, such as: water purification, carbon sequestration, nutrient cycling and the provision of habitats for biodiversity (Bünemann et al., 2018). Translating these multiple functions into practical indicators and approaches for soil and nutrient management remains challenging (Bünemann et al., 2018; Rinot et al., 2019). Incentivizing multi-objective management is also difficult when current management focuses on a single primary function, such as crop production. There is no ideal soil for everything, but purpose-driven evaluation of specific soil functions offers a more pragmatic route to soil health management (Vogel et al., 2019).

Carbon and nutrient inputs are important triggers for sustaining and improving soil health in crop production, which also increases the resilience of crop production systems to climate warming (Deng et al., 2020). Whereas in the past the emphasis in plant nutrition has been on soil fertility, i.e. the nutrient supplying capacity of soils, a new paradigm has to contribute to broader aspects of soil health. For example, sequestration of atmospheric CO_2 in soils can potentially contribute to reducing global warming and improving soil health, but it requires continuous inputs of organic material and nutrients (particularly N and P) to form stable soil organic matter, and having these nutrients available in the right places (van Groenigen et al., 2017; Spohn, 2020; Martin et al., 2021). How can a holistic plant nutrition approach manage macro- and micro-nutrients for high crop productivity and NuUE, 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 will mineral nutrition of crops change in changing climates?

Mineral nutrients in soils and crops have important and still difficult to predict positive as well as negative interactions with global climate change (Lynch and Clair, 2004; Soares et al., 2019), although negative impacts of climate change appear to outweigh positive ones (St.Clair and Lynch, 2010). Rising atmospheric CO_2 may increase crop yields, but it may also cause declining nutritional quality, particularly in crops that rely on C3-photosynthesis, such as wheat, barley, rice, soybean and others (Brouder and Volenec, 2017; Soares et al., 2019; Ebi et al., 2021). The mineral status of plants will become even more important under climate change-linked stress conditions. Balanced plant nutrition has particular roles in increasing the tolerance to drought (Waraich et al., 2011), heat (Mengutay et al., 2013; Sarwar et al., 2019) or high radiation (Marschner and Cakmak, 1989), and can thus be an important tool for managing climatic risks. Several nutrients are also directly involved in reducing pathogenic infection and increasing disease resistance of crop plants (Wang et al., 2013; Elmer and Datnoff, 2014; Cabot et al., 2019), mainly by improving cell wall stability and increasing the pool of defense metabolites against pathogen attack (Marschner, 2012). Changes in seasonality, precipitation and extreme weather events will 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?

In 2015, annual food-system GHG emissions amounted to 18 Gt CO_2 equivalent, representing 34% of total global GHG emissions (Crippa et al., 2021). About 71% of that came from agricultural production and land use. Therefore, all pathways that limit global warming to well below 2 °C require land-based mitigation and land-use change (IPCC, 2019). Improvements in the efficiency of agricultural production processes and reductions in land conversions have led to fairly stable levels of total GHG emissions from agriculture production and land use over the last 30 years, resulting in a 35% decrease on a per capita basis (Crippa et al., 2021). At issue is, what more can be done across the entire nutrient chain to reduce agricultural GHG emissions, including fertilizer production (Scope 1 and Scope 2 emissions), farm management of nutrients (Scope 3 emissions) and nutrient recycling. At present, energy use in ammonia synthesis alone accounts for more than 1% of global GHG emissions (measured in carbon dioxide equivalents).

Besides decarbonizing the industrial production of fertilizers, farm gate emissions of nitrous oxide (N_2O) from mineral and organic fertilizers are of particular interest because they amount to about 0.6 $GtCO_2e$ and 1.0 $GtCO_2e$, which together comprises nearly 10% of total food and land use GHG emissions (based on FAO data released in 2021). They can be reduced through a range of interventions, including novel fertilizer products and improved agronomic practices (Maaz et al., 2021), and addressing them may have greater leverage than soil carbon gains achievable from agricultural practice changes (Lawrence et al., 2021). Farmer awareness is however low and often limited by critical barriers (Gomes and Reidsma, 2021). Sequestration of atmospheric CO_2 in soils can also contribute to reducing global warming and improving soil health. However, the mitigation potential of practices such as conservation agriculture or crop residue incorporation has often been overstated (Poulton et al., 2018; Corbeels et al., 2020). The process would require increased biomass production for continuous organic matter inputs, balanced nutrient inputs of nitrogen, phosphorus and sulfur (Kirkby et al., 2016; Huang et al., 2020; Spohn, 2020), reducing soil disturbance and preventing erosion to form stable soil organic matter. Social, economic, and verification impediments would also need to be overcome (Amundson and Biardeau, 2018). Besides wanting to sequester more carbon from the atmosphere, an immediate need is to actually prevent further soil carbon losses because global warming may further accelerate the decomposition of soil organic matter (Nottingham et al., 2020).

(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 (e.g. iron, zinc, iodine, selenium), which increases child mortality, childhood stunting, anemia and susceptibility to many infectious diseases, but also affects many cognitive functions. In Africa, correlations can be found between soil nutrients and child mortality, stunting, wasting and underweight (Berkhout et al., 2019). In 2011 3.5 billion people were at risk of calcium (Ca) deficiency due to inadequate dietary supply, mostly in Africa and Asia (Kumssa et al., 2015). Current agricultural practices have also contributed to a decline in dietary potassium (K) intake and rise in hypokalemia prevalence in the US population (Sun and Weaver, 2020).

Cereals alone are grown on half of the world's cropland and they also consume half of the world's fertilizer. They are hugely important for human nutrition as major sources of dietary energy, essential proteins, mineral elements, and diverse bioactive food components (Poole et al., 2020). However, mineral nutrient concentrations of cereal crops appear to have declined in recent decades due to higher yields, narrower crop genetics, and/or soil nutrient depletion (Fan et al., 2008). Thus far, at global scale the benefits of increased yield to supply more food for expanding populations appear to outweigh such nutrient dilution effects (Marles, 2017). On the other hand, increasing cereal grain food processing results in Mg loss and reduced dietary Mg intake worldwide (Rosanoff and Kumssa, 2020). A handful of micronutrient-poor crops dominate the global food and feed chains and have often also decreased crop diversity or displaced traditional crops with higher nutrient density, such as pulses (Welch et al., 2013). What plant nutrition solutions can be effectively deployed at large scales to improve human nutrition through more nutritious crops and cropping systems? Who should pay for that?

(10) How can we better monitor nutrients and implement nutrient stewardship?

Numerous efforts have been made in recent years to develop and evaluate indicators for nutrient performance in fields and farms (Quemada et al., 2020), at national (Karimi et al., 2020) and at global scale (Zhang et al., 2015). Assessing nutrient footprints (Einarsson and Cederberg, 2019) or GHG emissions (Walling and Vaneeckhaute, 2020) and life cycles (Hasler et al., 2015) of different types of fertilizers have also become more common, including in industry. Governments have increasing requirements for monitoring progress against Sustainable Development Goals (SDGs), including nutrient-related targets and indicators in SDG 2 (Gil et al., 2019) and others. At global level, an International Code of Conduct for the Sustainable Use and Management of Fertilizers has recently been published by FAO (22). In industry, companies have increasing requirements for Environmental, Social, and Governance (ESG) monitoring and reporting to demonstrate higher levels of transparency, traceability, quality control, accountability and sustainability throughout all business areas.

At issue is how all these diverse efforts can be made more coherent and operational, and how the underlying data can be improved to reduce the huge uncertainties associated with even basic information on nutrient use and NuUE (Zhang et al., 2021b). Of particular importance are efforts to benchmark NuUE for individual fields because those are often more useful than looking at average balances for whole farms or aggregated over larger spatial scales. Field-level indicators are most useful for farmers to diagnose their fields in relation to the level of yield for a given level of nutrient input and management practice (and vice versa), serving as a concrete starting point to identify pathways for improvement (Tenorio et al., 2020).

Digital technologies offer great potential for better monitoring, analysis, benchmarking, reporting and certification of sustainability efforts across the entire nutrient chain, including tracking the impact of better practices, technologies and policies. This will become critical for business transformation, evidence-based policy making, and stakeholder communication.

3. Responsible plant nutrition: key elements of a new paradigm

Mineral nutrients play a central role in agricultural production as well as natural ecosystems. Impressive progress has been made in understanding the mechanisms of nutrient cycling and their functions in microbial and plant metabolism (Marschner, 2012). Human requirements and mass balance principles also make it clear that fertilizers will continue to be major ingredients of more sustainable food systems. However, future plant nutrition must meet multiple objectives that directly and indirectly contribute to many of the SDGs that now guide humanity (Ladha et al., 2020). Integrated, tailored plant nutrition strategies and practices need to minimize tradeoffs between productivity and the environment, and they need to be viable in the farming and business systems of different nations and localities. Integration in this context has several dimensions: a multi-nutrient food system approach, greater recycling and utilization of all available nutrient sources, alignment with agronomic and stewardship practices, and compliance with high sustainability standards.

Therefore, as a key element of sustainable intensification of crop production, the new paradigm for 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, utilization and recycling of mineral nutrients in agri-food systems. Following a food systems and circular economy approach, responsible plant nutrition aims to (Fig. 3):

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

Besides applying nutrients in the right manner, it also entails other measures that contribute to optimizing nutrient flows. Crop genetic improvement, better crop rotations, legumes, soil tillage, liming, residue management, water management, pests and diseases management, livestock, nutrient recycling from waste streams, data and effective information transfer are all important measures for reducing nutrient losses and increasing NuUE. Responsible plant nutrition will contribute much to a more nature-positive approach of food production and consumption that has recently been proposed. We note, however, that the latter requires a much clearer definition and that it should not aim to blindly copy nature because nature has not been optimized for human food production. On the other hand, many proven, good agronomic practices are not that different from commonly proposed agroecological principles (FAO, 2018; Wezel et al., 2020), and should therefore be adapted more widely.

Below we elaborate on six key actions required to implement responsible plant nutrition worldwide. We also refer to several specific examples, which are described in greater detail in the Supplementary Information document.

3.1. Action 1: Sustainability-driven nutrient roadmaps

We define nutrient roadmaps as a combination of sustainability-driven policies, technologies and business models that aim to optimize nutrient use and NuUE in agriculture within each country in the next 10–20 years. They by and large don't exist yet. They must be linked to the SDGs and tailored to the specific food systems and natural endowments in every country, with ambitious but realistic targets for NuUE as the key driver for productivity and reduced nutrient losses. For nitrogen, for example, spatially explicit boundaries can be defined to meet air and water quality targets, while also having to meet minimum production requirements (Vries et al., 2021). Nutrient monitoring, nutrient stewardship principles (International Plant Nutrition Institute, 2016) and new sustainability standards (e.g. sustainable sourcing and certification schemes) will increasingly guide policy making, business innovation and

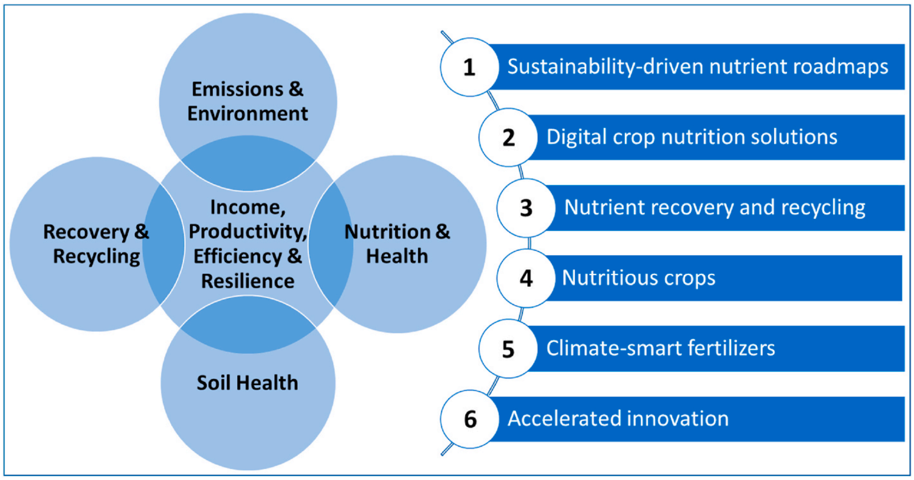

Fig. 3. The five interconnected aims (left) of the new paradigm for responsible plant nutrition, and six key actions to take (right).

farming practices.

Specific targets and priorities for designing such nutrient roadmaps and managing nutrients will vary, depending on each country's agricultural sectors, natural capital, nutrient use history and sustainable development priorities. Once fertilizers become readily available and other technologies enable a better crop yield response, farms and countries typically move along a common trajectory over many decades, but at varying speed (Fig. 4). The current position of several countries or world regions is shown for illustrative purposes.

At the early stages of economic development (Phase A in Fig. 4), fertilizer use, often done through blanket applications, rises from a very low level and drives crop yields and farming profits. Hence, starting from very high NuUE levels that actually represent a situation of soil mining, NuUE declines and nutrient surplus starts to grow (Fig. 4). Many countries in sub-Saharan Africa are still at the upper left end of this trajectory. Their first priority must be to increase fertilizer use in order to jump-start crop yield growth (Vanlauwe and Dobermann, 2020), but do it as part of an integrated soil fertility management approach that utilizes all available resources and focuses on local adaptation of agronomic interventions (see SI Example 1).

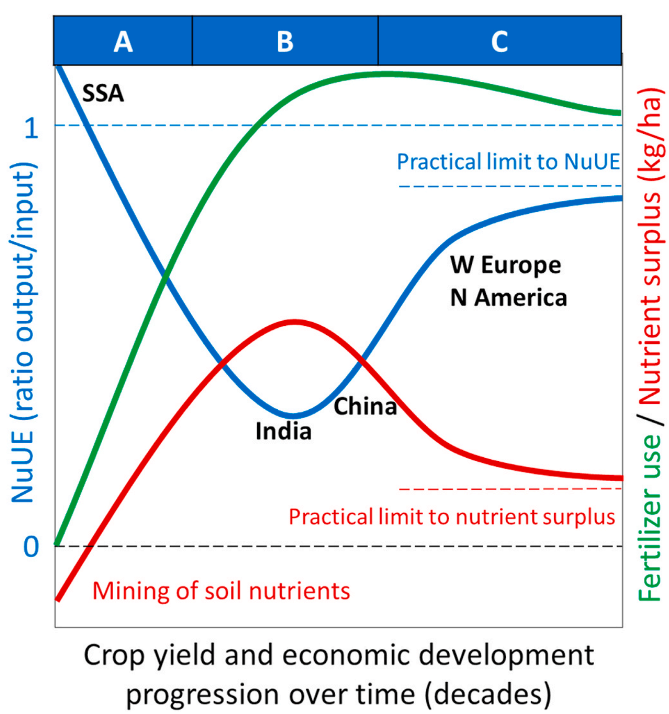

Fig. 4. Generalized development pathway for nutrient use efficiency (NuUE) in crop production. The green line represents the general evolution in fertilizer use over many decades. The blue curve shows the typical progression of NuUE (defined as the nutrient output/nutrient input ratio) in a country, region or farm over time, whereas the red curve illustrates the corresponding nutrient surplus and risk of environmental pollution. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Historically, this then leads to a longer intensification period (Phase B in Fig. 4) during which fertilizer use and crop yields rise further, but NuUE declines even more and nutrient surpluses may become excessive. Often this is also caused by sustained fertilizer subsidies, which provide little incentive for balanced fertilizer use and optimizing NuUE. India is a good example for that, where numerous fertilizer price regulating and subsidy schemes have played a major role in driving fertilizer consumption since the 1970s (see SI Example 2.) As a result, N and P fertilizer use on cropland in India more than doubled, but the use efficiency of these nutrients declined to about 30–40% and has remained virtually unchanged at that low level. In that situation the top priority is a shift towards smarter policies that provide clear incentives to increase NuUE.

Towards the end of Phase B, due to rising environmental and public health concerns, the political pressure increases and countries begin to take mitigation measures, including stricter regulation to limit nutrient use. China has entered this phase in recent years through its new green development priorities (see SI Example 3). The new policies now limit fertilizer use and focus on better technologies and agronomic practices. Consequently, NuUE has started to increase again in China in recent years (Fig. 4). That is when farms and countries start moving into phase C, which is characterized by a mix of mandatory regulation, voluntary schemes, new technologies and precision nutrient management practices becoming more widely adopted by farmers. Nutrient stewardship schemes play an increasing role in all that, which, for example, have been successfully promoted by the fertilizer industry and other stakeholders in North America (see SI Example 4).

The emphasis in phase C is on enabling continued growth of crop yields and profitability through rising NuUE, while decreasing the nutrient surplus. In practice, this may result in stagnating or even declining fertilizer consumption, as has been the case for most of Western Europe and North America in recent decades. But there are limits for the NuUE and nutrient surpluses that can be achieved, i.e. farms and countries will slowly but steadily approach biophysical and socioeconomic limits (Fig. 4). Countries, businesses and farmers can do much to move faster towards those limits. The latter also represent ambitious but realistic targets to aim for in a particular mix of farming systems. The NUE indicator developed by the European Nitrogen Expert Panel is an excellent analytical tool for monitoring the performance of a farm (or a country) relative to an optimal zone in which high N output (crop yield) is achieved with high NUE and low N surplus (see SI Example 5). It provides a sound basis for setting targets, benchmarking farms or regions, and monitoring progress over time. Besides improving NuUE at the field and farm level, it is important to recognize that nutrient pollution for a region (e.g., indicated by a large nutrient surplus shown in Fig. 1) is also affected by the nutrient application rate and the extent of crop production in the region, as well as the legacy effect of nutrient applications in previous years and decades (Quan et al., 2021). For example, even though the USA has made significant progress in improving NUE, the N surplus level for the Corn Belt is still high. Therefore, further reduction in regional nutrient pollution may require efforts beyond field-level NUE improvement and may take time to become tangible.

In summary, targets, roadmaps and specific solutions for nutrients will differ among regions and countries. In many (Zone C in Fig. 4), decoupling of agricultural productivity growth from growth in fertilizer use is already ongoing and NuUE has been increasing substantially (e.g. North America, Western Europe, Japan), but there is still a gap to close. In others (Zone B), decoupling must accelerate to close large NuUE gaps and reduce nutrient pollution faster. In yet others (Zone A), coupling is needed to increase crop yields and improve soil health through increasing nutrient inputs, but doing so in a sustainable manner. Differentiated nutrient roadmaps will thus also lead to regional shifts in fertilizer use, reducing nutrient surpluses in countries in some countries while ensuring that more nutrients are moved to where they are most lacking (Fig. 1), particularly to many parts of Africa (Zhang, 2017). A critical issue to resolve is how to develop context-specific targets and roadmaps for responsible nutrient use in a country or agricultural sector. Participatory backcasting approaches may be of particular interest for such purposes (Kanter et al., 2016).

3.2. *Action 2: Digital crop nutrition solutions*

On their own, smart phones or other digital tools cannot achieve good crop nutrition in the field because the latter will always depend on farmers making the right decisions. However, data- and knowledge-driven digital solutions and technologies will increasingly allow tailoring nutrient applications to local needs in a more precise manner, and reaching many more farmers than a few agronomists could do on their own. New soil and crop diagnostic tools and sensors, high-resolution soil, crop and climate data, mechanistic real-time prediction models, and artificial intelligence-based decision support are all expected to play an increasing role in responsible plant nutrition, provided that they are robust in performance and of real benefit to farmers.

Of particular promise are approaches that harness data to accelerate the process of optimizing crop and soil management practices that govern both yields and nutrient use efficiency at production scale (Cassman and Grassini, 2020; Mulders et al., 2021). Artificial intelligence approaches will play an increasing role in developing self-learning fertilizer advisory solutions, particularly once it becomes possible to move seamlessly from data to prescriptive analytics and automated decision making with less human interference (Smith, 2020).

Besides high-tech solutions for commercial farming, 'low-tech' site-specific nutrient management (SSNM) approaches have shown consistent, large increases in crop yields and profits and NUE in many crops grown by smallholder farmers in Asia and Africa (see SI Example 6). Across a wide range of countries and environments, relative to the farmer practice, SSNM in rice, wheat and maize increased grain yield by 12% and profitability by 15% with 10% less fertilizer nitrogen applied (Chivenge et al., 2021). Upscaling this to millions of farmers requires digitally supported advisory systems and viable business solutions.

Worldwide, only 24–37% of farms of $<$1 ha in size are served by third generation (3G) or 4G services, compared to 74–80% of farms of $>$200 ha in size, and croplands with severe yield gaps, climate-stressed locations and food-insecure populations often have poor service coverage (Mehrabi et al., 2020). This gap needs to be overcome for more knowledge-based, digital information, advisory and market integration solutions to reach impact at large scale. A lot can also be gained by working at scales above fields and farms, i.e. at landscape and national levels in terms of targeting better fertilizer specific formulations and crop specific application recommendations, particularly in smallholder farming (Xu et al., 2019).

3.3. *Action 3: Nutrient recovery and recycling*

Food systems and circular economy strategies require actions at different stages and scales to optimize NuUE for the full nutrient chain (from soil to plate and back to soil). Hence, better crop-livestock integration, less food (nutrient) waste and increased nutrient recovery and recycling for higher nutrient use efficiency will play increasing role in the responsible plant nutrition paradigm (Fig. 5). This is an area of exciting developments, including numerous researchers and startup companies working on specific technologies and business solutions. Political incentives, novel technologies and shifts in behavior will drive even greater efforts on nutrient recovery and recycling from multiple waste streams, as a key contribution to circular bio-based economies (see SI Example 7 for a more detailed discussion).

Such circular systems need to be safe and healthy for animals, humans and the environment, and also allow the creation of sustainable business models. System designs that fit into practice will have to meet numerous principles and criteria (Cordell et al., 2011; Muscat et al., 2021), also to facilitate decision-making by different stakeholders involved (Vaneeckhaute, 2021). While a circular bio-economy requires connected sectors, examples of single sector circularity are major first steps. Such examples include the reuse of side-streams within the agricultural sector and up-cycling of materials, which are relevant in the context of responsible plant nutrition.

Besides tighter integration of crop and livestock production, closing nutrient cycles will also require recovering more nutrients from human excreta and waste, particularly also in developing countries. Good potential exists for this through new technologies, but there are also significant sociocultural, infrastructure and other challenges to overcome (van der Hoek et al., 2018; Lohman et al., 2020; van der Kooij et al., 2020). Another concern is how to minimize contamination risks that may be associated with such waste streams, including heavy metals such as cadmium (Cd). Manure or sewage sludge tend to add more Cd over smaller areas of land compared to mineral or recycled granular fertilizers that add smaller amounts over much larger land areas. Significant advances have been made in understanding the behavior of Cd in agricultural systems and a range of management options are now available for farmers to minimize Cd uptake into crops and forages. (McLaughlin et al., 2021). It has also been proposed that the use of recycled fertilizers should be regulated based on their pollutant-to-nutrient ratio (Weissengruber et al., 2018). Composts, for example, may present a greater risk due to low nutrient contents, i.e. higher application rates to achieve the same nutrient input.

Overall, this will lead to a more diversified, more decentralized production of recycled fertilizers that are expected to meet the standards of 'normal' mineral fertilizers, including having equivalent agronomic performance (Huygens and Saveyn, 2018; Huygens et al., 2020). Significant opportunities also exist for more microbial and other bio-based solutions to enhance nutrient supply, efficiency or recycling, as part of the growing bioeconomy. Improved full-chain nutrient flow monitoring, benchmarking and life-cycle analysis need to support the development of such solutions, along with certification and supporting as well as regulating policies. At present, government regulations are often too outdated and inconsistent among countries in order to properly enable these new developments. This presents a huge barrier for accelerating investment and upscaling.

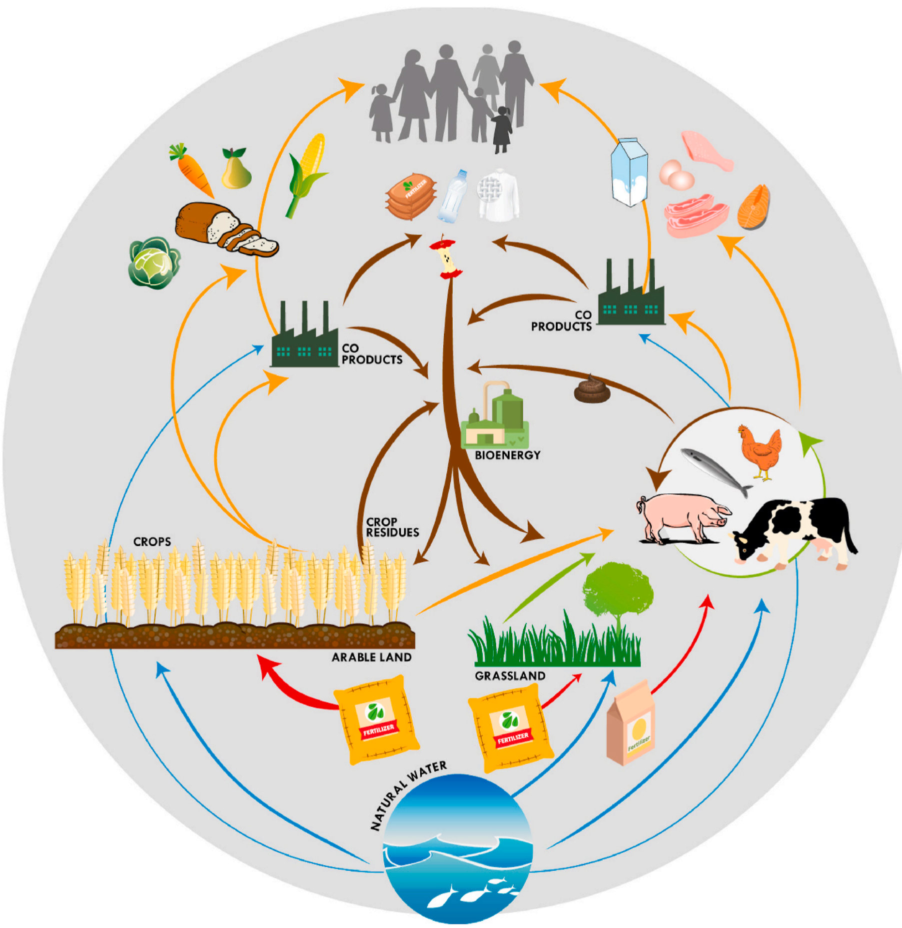

Fig. 5. Major nutrient flows in circular crop-livestock-human systems. Red arrows indicate fertilizer inputs into the system. Fertile land is primarily used to produce food for humans and some supplementary feed for livestock, also from crop residues (orange arrows). Grassland is primarily used for livestock, 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: Redrawn and modified from (van Zanten et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Action 4: Nutritious crops

Fertilizer programs implemented in the past mainly focused on improving soil fertility and crop yields as well as farm incomes, with main emphasis given to N, P and K fertilizers. Little or no priority has been given to nutritional outcomes for human health. Responsible plant nutrition solutions must also consider the whole nutritional contribution of food crops, towards addressing the triple burden of undernutrition, micronutrient malnutrition, overweight/obesity and non-communicable diseases (Poole et al., 2020).

In principle, the choice of what to eat and how much lies with consumers, which would then also create market demands to be met by growing different crops, including crops with better nutritional value. Depending on the local context, nutrition-sensitive crop production may include more diverse crop rotations, enhancing protein and micronutrient contents through N, P and K fertilizer management (Singh et al., 2018; Zhang et al., 2021a), as well as biofortification of staple crops with micronutrients through breeding and/or fertilizers (Cakmak and Kutman, 2018; Garg et al., 2018). The latter involves the targeted use of fertilizer products that deliver micronutrients of importance to crops, animals and humans, which is of particular relevance in regions where much of the food is grown and consumed locally. Enriching these crops with certain minerals has a direct impact on human health without any change in actual consumer behavior. Besides essential plant nutrients such as iron or zinc, this should increasingly include nutrients that are of particular importance to animals and humans, such as iodine (Fuge and Johnson, 2015) or selenium (Alfthan et al., 2015). End-to-end connectivity and traceability will be important elements of such a strategy.

Biofortification of staple crops with micronutrients offers cost-effective opportunities for combating micronutrient malnutrition (Meenakshi et al., 2010). At issue is where will this be most effective, and how it can be mainstreamed into agriculture, particularly if farmers do not get paid for such additional food quality value. Finland, for example, is the only country in the world in which all crop fertilizers must contain 10–15 mg selenium kg^{-1} (Alfthan et al., 2015). This mandatory practice was introduced in 1985 because Finnish soils were low in available Se and so was the Se concentration in the blood plasma of Finns. This fertilizer enrichment practice has led to a 15-fold increase in selenium concentration of spring cereals, resulting in effective and safe increases in selenium intake and health of the whole population (Fig. 6). Similar results have been obtained through fertilizer-based fortification of maize in Malawi (Chilimba et al., 2012), and in many other crop-nutrient combinations (see SI Example 8).

An important issue is to also update regulatory approaches for fertilizers in order to justify and encourage more investments in nutritionally enhanced fertilizers solutions. Current definitions of essential or beneficial elements for plant growth are partially outdated and even compromise fertilizer regulation and practice. A new definition has recently been proposed, which is better aligned with nutrients deemed essential or beneficial for crops, animal and humans, thus following a more holistic 'one nutrition' concept (Brown et al., 2021).

At the same time it is vital that impurities in fertilizers do not adversely affect soil or food quality, with cadmium being the element requiring most careful management in mineral fertilizers (Chaney, 2012). For fertilizers manufactured from recycle or waste streams, there are a range of contaminants that must be considered and managed to ensure the production of clean food and to avoid soil pollution. Improving micronutrient concentrations in food crops would also be useful in reducing intestinal absorption and retention of heavy metals such as cadmium in the body (Reeves and Chaney, 2008).

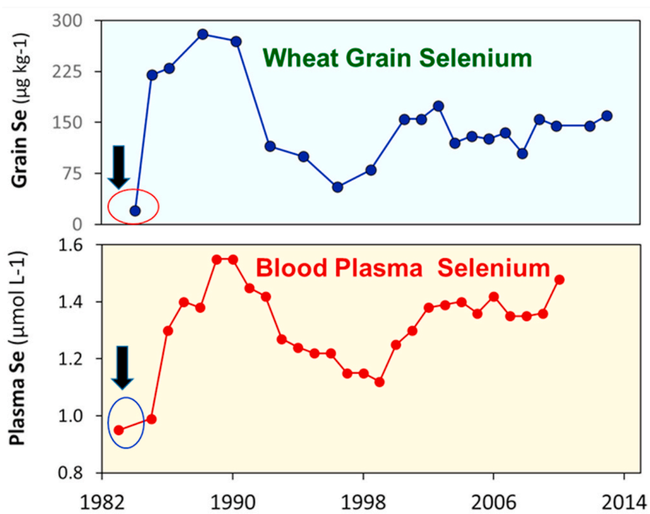

Fig. 6. Changes in wheat grain and blood selenium in healthy Finns since Se-enrichment of NPK fertilizers was introduced in 1985. Source: re-drawn from (Alfthan et al., 2015).

3.5. Action 5: Climate-smart 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 (see SI Example 9). Across the plant nutrition sector, low-emission fertilizer production and transportation technologies, novel fertilizer formulations or inhibitors, as well as more precise nutrient application and agronomic field management (van Loon et al., 2019; Maaz et al., 2021) offer opportunities to directly and indirectly reduce fertilizer-related emissions of CO_2 and N_2O, provided that the surrounding market conditions and policies enable that. Significant reductions in pre-farm GHG emissions can be achieved by utilizing renewable energy in fertilizer production. Decarbonizing ammonia production has become a particular necessity and opportunity in the fertilizer industry (IEA, 2021), with various new technologies being piloted to produce 'green ammonia' from carbon-neutral energy sources, but also use ammonia for energy storage and transport. Such a new ammonia economy has the potential to feed and power the world in a whole new and perhaps even more decentralized manner (Rouwenhorst et al., 2019).

Innovation in fertilizer technology and formulation will lead to environmentally-friendly fertilizers that maximize nutrient capture by the crop and minimize losses of nutrients (see SI Example 9). Important innovation areas include bio-based coatings (Chen et al., 2018), 'smart fertilizers' where nutrients are released from granules on contact with plant roots (Zhang et al., 2013), and a whole range of new materials (e.g. nanomaterials, graphene, metal-organic frameworks, etc.) offering pathways for tailoring nutrient release to be more in synchrony with plant demand. Progress is also being made in other innovation areas that could lead to specific improvements in NuUE, for example through new microbial formulations that are based on a deeper understanding of the soil-plant microbiome (Fierer, 2017), or the use of biostimulants (Rouphael and Colla, 2020). As with all new technologies, the challenge is to introduce these innovations into the market so that they can be manufactured easily, are cost and quality competitive at farm level, perform reliably and will be safe. Risks and benefits need to be evaluated thoroughly and independently in field studies, particularly with regard to environmental or health risks that may be associated with technologies such as nano-fertilizers (Dimkpa and Bindraban, 2018; Hofmann et al., 2020). Robust, evidence-based regulatory approaches have to be developed to enable safe and wider use of many of these new products.

3.6. Action 6: Accelerated innovation

Future plant nutrition research and innovation needs to foster co-creation and sharing of knowledge for more rapid development and deployment of new technologies and better practices at scale. There are major knowledge gaps that require re-orienting research investments at global and regional scales towards issues that are most critical for developing the right nutrient roadmaps and solutions. For example, proper benchmarking of the main cropping systems at global level is an important innovation area to identify priority areas and suitable solutions for increasing yields and nutrient use efficiency in parallel. Unfortunately, examples of this type of field-based assessments with the required level of granularity and agronomic context are still scarce (Yuan et al., 2021).

Besides more investment by both public and private sector, accelerating innovation also requires more openness, sharing of data and other resources, and coordinated action of public and private sector players in agricultural innovation (Berthet et al., 2018). A massive culture change is needed in science and science funding, towards a problem-focused and leaner science approach, transdisciplinary collaborations, use of digital tools, entrepreneurship, and early and frequent engagement with key stakeholders and end users, including farmers in particular (Karp et al., 2015; Herrero et al., 2020).

4. Who needs to do what?

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. 7).

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. This is particularly important as many farmers currently perceive the continuous change of laws and regulations as one of their main challenges (Paas et al., 2021). Policy makers 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 (International Fertilizer Association, 2018). 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 for them.

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

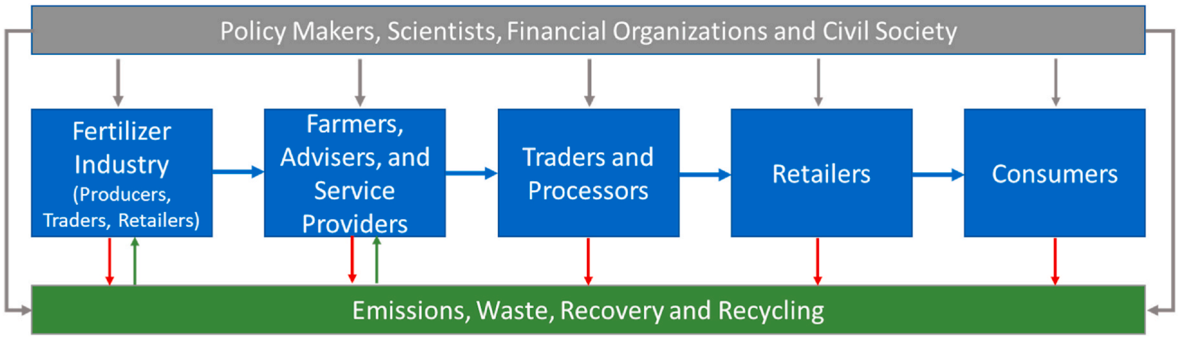

Fig. 7. The agri-food chain from a nutrient management perspective. Blue boxes show actors who directly contribute to nutrient use and losses at different stages. Red arrows indicate greenhouse gas emissions, nutrient losses into the environment and waste that can happen in all parts of the chain. All 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 primary actors, drive innovation or set the societal framework for action. Source: Modified from (Kanter et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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.

5. Conclusions: a vision of success

The coming 10–20 years will be of major importance for transforming the world's nutrient cycles and management systems, across the entire nutrient and fertilizer value chain. The primary change will be a new societal plant nutrition optimum rather than a purely economic optimum, which, most importantly must also benefit farmers and all other primary actors in the nutrient chain. The implication is that society as a whole will need to share more of the cost of achieving the desired societal (environmental) outcomes, but the mechanisms for that are far from clear. In any case, the new nutrient economy will have to become an integral component of a low carbon emission, nature-positive and circular food system that supports a rising global population. 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 bioindustry demand and outpaces growth in mineral fertilizer consumption, while cropland expansion and deforestation have been halted. Global crop NUE – 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 P 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. 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.

Such outcomes can be best met through strategies that integrate more efficient food production practices with healthier diets, wasting less, recycling more and appropriate level of trade. Achieving them now, within one human generation, will require significant investments and a far more concerted effort by everyone involved, from the fertilizer industry to farmers and consumers of food and other agricultural products.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

All members of the Scientific Panel on Responsible Plant Nutrition (SPRPN) have contributed equally to this paper. Opinions expressed in this article are those of the individual members of the panel, not that of the organizations they work for. An earlier, short version of this paper was previously published as an Issue Brief by the SPRPN and is available at www.sprpn.org.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2022.100636.

References

Alfthan, G., Eurola, M., Ekholm, P., Venäläinen, E.-R., Root, T., Korkalainen, K., Hartikainen, H., Salminen, P., Hietaniemi, V., Aspila, P., Aro, A., 2015. Effects of nationwide addition of selenium to fertilizers on foods, and animal and human health in Finland: from deficiency to optimal selenium status of the population. J. Trace Elem. Med. Biol. 31, 142–147.

Amundson, R., Biardeau, L., 2018. Opinion: soil carbon sequestration is an elusive climate mitigation tool. Proc. Natl. Acad. Sci. U. S. A 115, 11652–11656.

Assefa, B.T., Reidsma, P., Chamberlin, J., van Ittersum, M.K., 2021. Farm- and community-level factors underlying the profitability of fertiliser usage for Ethiopian smallholder farmers. Agrekon 60, 460–479.

Berge, H.F.M. ten, Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., Groot, H.L.E.de, van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. Global Food Secur. 23, 9–21.

Berkhout, E.D., Malan, M., Kram, T., 2019. Better soils for healthier lives? An econometric assessment of the link between soil nutrients and malnutrition in Sub-Saharan Africa. PLoS One 14, e0210642.

Berthet, E.T., Hickey, G.M., Klerkx, L., 2018. Opening design and innovation processes in agriculture: insights from design and management sciences and future directions. Agric. Syst. 165, 111–115.

Biermann, F., Kim, R.E., 2020. The boundaries of the Planetary Boundary framework: a critical appraisal of approaches to define a "safe operating space" for humanity. Annu. Rev. Environ. Resour. 45, 497–521.

Brouder, S.M., Volenec, J.J., 2017. Future climate change and plant macronutrient use efficiency. In: Hossain, M.A., Kamiya, T., Burritt, D.J. (Eds.), Plant Macronutrient Use Efficiency. Molecular and Genomic Perspectives in Crop Plants. Academic Press, London United Kingdom, pp. 357–379.

Brown, P.H., Zhao, F.-J., Dobermann, A., 2021. What is a Plant Nutrient? Changing Definitions to Advance Science and innovation in Plant Nutrition. Plant Soil. https://doi.org/10.1007/s11104-021-05171-w.

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., Deyn, G.de, Goede, R.de, Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125.

Cabot, C., Martos, S., Llugany, M., Gallego, B., Tolr├á, R., Poschenrieder, C., 2019. A role for zinc in plant defense against pathogens and herbivores. Front. Plant Sci. 10, 1171.

Cakmak, I., Kutman, U.B., 2018. Agronomic biofortification of cereals with zinc: a review. Eur. J. Soil Sci. 69, 172–180.

Cassman, K.G., Dobermann, A., 2022. Nitrogen and the future of agriculture: 20 years on. Ambio 51, 17–24.

Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. Nat. Sustain. 3, 262–268.

Chaney, R.L., 2012. Food safety issues for mineral and organic fertilizers. Adv. Agronomy 117, 51–116.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., Zhang, F., 2014. Producing more grain with lower environmental costs. Nature 514, 486–489.

Chen, J., Lü, S., Zhang, Z., Zhao, X., Li, X., Ning, P., Liu, M., 2018. Environmentally friendly fertilizers: a review of materials used and their effects on the environment. Sci. Total Environ. 613–614, 829–839.

Chilimba, A.D., Young, S.D., Black, C.R., Meacham, M.C., Lammel, J., Broadley, M.R., 2012. Agronomic biofortification of maize with selenium (Se) in Malawi. Field Crop. Res. 125, 118–128.

Chivenge, P., Saito, K., Bunquin, M.A., Sharma, S., Dobermann, A., 2021. Co-benefits of nutrient management tailored to smallholder agriculture. Global Food Secur. 30, 100570.

St Clair, S.B, Lynch, J.P., 2010. The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. Plant Soil 335, 101–115.

Corbeels, M., Cardinael, R., Powlson, D., Chikowo, R., Gerard, B., 2020. Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated. Soil Tillage Res. 196, 104300.

Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L., 2011. Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. Chemosphere 84, 747–758.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2, 198–209.

Deng, X., Huang, Y., Qin, Z., 2020. Soil indigenous nutrients increase the resilience of maize yield to climatic warming in China. Environ. Res. Lett. 15, 94047.

Dimkpa, C.O., Bindraban, P.S., 2018. Nanofertilizers: new products for the industry? J. Agric. Food Chem. 66, 6462–6473.

Ebi, K.L., Anderson, C.L., Hess, J.J., Kim, S.-H., Loladze, I., Neumann, R.B., Singh, D., Ziska, L., Wood, R., 2021. Nutritional quality of crops in a high CO_2 world: an agenda for research and technology development. Environ. Res. Lett. 16, 64045.

Einarsson, R., Cederberg, C., 2019. Is the nitrogen footprint fit for purpose? An assessment of models and proposed uses. J. Environ. Manag. 240, 198–208.

Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J., Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V. K., van Saun, R., Winter, M., 2014. Agriculture: steps to sustainable livestock. Nature 507, 32–34.

Elmer, W.H., Datnoff, L.E., 2014. Mineral nutrition and suppression of plant disease. In: van Alfen, N.K. (Ed.), Encyclopedia of Agriculture and Food Systems. Elsevier/ Academic Press, Amsterdam, pp. 231–244.

Erisman, J., Leach, A., Bleeker, A., Atwell, B., Cattaneo, L., Galloway, J., 2018. An integrated approach to a nitrogen use efficiency (NUE) indicator for the food production–consumption chain. Sustainability 10, 925.

Fan, M.-S., Zhao, F.-J., Fairweather-Tait, S.J., Poulton, P.R., Dunham, S.J., McGrath, S.P., 2008. Evidence of decreasing mineral density in wheat grain over the last 160 years. J. Trace Elem. Med. Biol. 22, 315–324.

FAO, 2018. The 10 Elements of Agroecology. Guiding the Transition to Sustainable Food and Agricultural Systems. http://www.fao.org/3/i9037en/i9037en.pdf.

FAO, 2021. The State of the World's Land and Water Resources for Food and Agriculture – Systems at Breaking Point. Synthesis Report. FAO, Rome.

Fierer, N., 2017. Embracing the unknown: disentangling the complexities of the soil microbiome. Nat. Rev. Microbiol. 15, 579.

FOLU, 2019. Growing better: ten critical transitions to transform food and land use. The Food and Land Use Coalition. https://www.foodandlandusecoalition.org/global-report/.

Forber, K.J., Rothwell, S.A., Metson, G.S., Jarvie, H.P., Withers, P.J.A., 2020. Plant-based diets add to the wastewater phosphorus burden. Environ. Res. Lett. 15, 94018.

Fuge, R., Johnson, C.C., 2015. Iodine and human health, the role of environmental geochemistry and diet, a review. Appl. Geochem. 63, 282–302.

Fuglie, K.O., 2018. Is agricultural productivity slowing? Global Food Secur. 17, 73–83.

Garg, M., Sharma, N., Sharma, S., Kapoor, P., Kumar, A., Chunduri, V., Arora, P., 2018. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Front. Nutr. 5, 12.

Gil, J.D.B., Reidsma, P., Giller, K., Todman, L., Whitmore, A., van Ittersum, M., 2019. Sustainable development goal 2: improved targets and indicators for agriculture and food security. Ambio 48, 685–698.

Gomes, A., Reidsma, P., 2021. Time to transition: barriers and opportunities to farmer adoption of soil GHG mitigation practices in Dutch agriculture. Front. Sustain. Food Syst. 5, 335.

Grote, U., Craswell, E., Vlek, P., 2005. Nutrient flows in international trade: ecology and policy issues. Environ. Sci. Pol. 8, 439–451.

Guo, Y., Chen, Y., Searchinger, T.D., Zhou, M., Pan, D., Yang, J., Wu, L., Cui, Z., Zhang, W., Zhang, F., Ma, L., Sun, Y., Zondlo, M.A., Zhang, L., Mauzerall, D.L., 2020. Air quality, nitrogen use efficiency and food security in China are improved by cost-effective agricultural nitrogen management. Nature Food 1, 648–658.

Hasler, K., Bröring, S., Omta, S., Olfs, H.-W., 2015. Life cycle assessment (LCA) of different fertilizer product types. Eur. J. Agron. 69, 41–51.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science (New York, N.Y.) 327, 822–825.

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., Boer, I.J.M. de, Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C., 2020. Innovation can accelerate the transition towards a sustainable food system. Nature Food 1, 266–272.

Hofmann, T., Lowry, G.V., Ghoshal, S., Tufenkji, N., Brambilla, D., Dutcher, J.R., Gilbertson, L.M., Giraldo, J.P., Kinsella, J.M., Landry, M.P., Lovell, W., Naccache, R., Paret, M., Pedersen, J.A., Unrine, J.M., White, J.C., Wilkinson, K.J., 2020. Technology readiness and overcoming barriers to sustainably implement nanotechnology-enabled plant agriculture. Nature Food 1, 416–425.

Huang, X., Terrer, C., Dijkstra, F.A., Hungate, B.A., Zhang, W., van Groenigen, K.J., 2020. New soil carbon sequestration with nitrogen enrichment: a meta-analysis. Plant Soil 454, 299–310.

Hutchings, N.J., Sørensen, P., Cordovil, C.M., Leip, A., Amon, B., 2020. Measures to increase the nitrogen use efficiency of European agricultural production. Global Food Secur. 26, 100381.

Huygens, D., Saveyn, H.G.M., 2018. Agronomic efficiency of selected phosphorus fertilisers derived from secondary raw materials for European agriculture. A meta-analysis. Agron. Sustain. Dev. 38.

Huygens, D., Orveillon, D., Lugato, E., Tavazzi, S., Comero, S., Jones, A., Gawlik, B., Saveyn, H., 2020. Technical Proposals for the Safe Use of Processed Manure above the Threshold Established for Nitrate Vulnerable Zones by the Nitrates Directive (91/676/EEC). Publications Office of the European Union, Luxembourg.

IEA, 2021. Ammonia Technology Roadmap. Towards More Sustainable Nitrogen Fertiliser Production. International Energy Agency (IEA), Paris, France.

International Fertilizer Association, 2018. IFA 2030 Scenarios. Digging Deeper, Thinking Harder, Planning Further. https://www.fertilizer.org/Public/About_IFA/IFA2030.aspx.

International Plant Nutrition Institute, 2016. 4R Plant Nutrition Manual: A Manual for improving the Management of Plant Nutrition. metric version. IPNI, Norcross, GA, USA.

IPCC, 2019. Climate Change and Land. IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. https://www.ipcc.ch/srccl/.

Kanter, D.R., Schwoob, M.H., Baethgen, W.E., Bessembinder, J., Carriquiry, M., Dobermann, A., Ferraro, B., Lanfranco, B., Mondelli, M., Penengo, C., Saldias, R., Silva, M.E., Lima, J.M.S.de, 2016. Translating the Sustainable Development Goals into action: a participatory backcasting approach for developing national agricultural transformation pathways. Global Food Secur. 10, 71–79.

Kanter, D.R., Bartolini, F., Kugelberg, S., Leip, A., Oenema, O., Uwizeye, A., 2020. Nitrogen pollution policy beyond the farm. Nature Food 1, 27–32.

Kao, P.T., Darch, T., McGrath, S.P., Kendall, N.R., Buss, H.L., Warren, H., Lee, M., 2020. Factors influencing elemental micronutrient supply from pasture systems for grazing ruminants. Adv. Agron. 164, 161–229.

Karimi, R., Pogue, S.J., Kröbel, R., Beauchemin, K.A., Schwinghamer, T., Henry Janzen, H., 2020. An updated nitrogen budget for Canadian agroecosystems. Agric. Ecosyst. Environ. 304, 107046.

Karp, A., Beale, M.H., Beaudoin, F., Eastmond, P.J., Neal, A.L., Shield, I.F., Townsend, B. J., Dobermann, A., 2015. Growing innovations for the bioeconomy. Nat. Plants 1, 15193.

Kinnunen, P., Guillaume, J.H.A., Taka, M., D'Odorico, P., Siebert, S., Puma, M.J., Jalava, M., Kummu, M., 2020. Local food crop production can fulfil demand for less than one-third of the population. Nature Food 1, 229–237.

Kirkby, C.A., Richardson, A.E., Wade, L.J., Conyers, M., Kirkegaard, J.A., 2016. Inorganic nutrients increase humification efficiency and C-sequestration in an annually cropped soil. PLoS One 11, e0153698.

Kumssa, D.B., Joy, E.J.M., Ander, E.L., Watts, M.J., Young, S.D., Walker, S., Broadley, M. R., 2015. Dietary calcium and zinc deficiency risks are decreasing but remain prevalent. Sci. Rep. 5, 10974.

Ladha, J.K., Jat, M.L., Stirling, C.M., Chakraborty, D., Pradhan, P., Krupnik, T.J., Sapkota, T.B., Pathak, H., Rana, D.S., Tesfaye, K., Gerard, B., 2020. Achieving the sustainable development goals in agriculture: the crucial role of nitrogen in cereal-based systems. Adv. Agron. 163, 39–116.

Lawrence, N.C., Tenesaca, C.G., VanLoocke, A., Hall, S.J., 2021. Nitrous oxide emissions from agricultural soils challenge climate sustainability in the US Corn Belt. Proc. Natl. Acad. Sci. U. S. A 118.

Lohman, H.A.C., Trimmer, J.T., Katende, D., Mubasira, M., Nagirinya, M., Nsereko, F., Banadda, N., Cusick, R.D., Guest, J.S., 2020. Advancing sustainable sanitation and agriculture through investments in human-derived nutrient systems. Environ. Sci. Technol. 54, 9217–9227.

Lynch, J.P., St Clair, S.B, 2004. Mineral stress: the missing link in understanding how global climate change will affect plants in real world soils. Field Crop. Res. 90, 101–115.

Ma, L., Bai, Z., Ma, W., Guo, M., Jiang, R., Liu, J., Oenema, O., Velthof, G.L., Whitmore, A.P., Crawford, J., Dobermann, A., Schwoob, M., Zhang, F., 2019. Exploring future food provision scenarios for China. Environ. Sci. Technol. 53, 1385–1393.

Maaz, T.M., Sapkota, T.B., Eagle, A.J., Kantar, M.B., Bruulsema, T.W., Majumdar, K., 2021. Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture. Global Change Biol. 27, 2343–2360.

Marles, R.J., 2017. Mineral nutrient composition of vegetables, fruits and grains: the context of reports of apparent historical declines. J. Food Compos. Anal. 56, 93–103.

Marschner, P. (Ed.), 2012. Marschner's Mineral Nutrition of Higher Plants, third ed. Academic Press, Amsterdam, London.

Marschner, H., Cakmak, I., 1989. High light intensity enhances chlorosis and necrosis in leaves of zinc, potassium, and magnesium deficient bean (Phaseolus vulgaris) plants. J. Plant Physiol. 134, 308–315.

Martin, M.P., Dimassi, B., Román Dobarco, M., Guenet, B., Arrouays, D., Angers, D.A., Blache, F., Huard, F., Soussana, J.-F., Pellerin, S., 2021. Feasibility of the 4 per 1000 aspirational target for soil carbon: a case study for France. Global Change Biol. 27, 2458–2477.

McArthur, J.W., McCord, G.C., 2017. Fertilizing growth: agricultural inputs and their effects in economic development. J. Dev. Econ. 127, 133–152.

McLaughlin, M.J., Smolders, E., Zhao, F.J., Grant, C., Montalvo, D., 2021. Managing cadmium in agricultural systems. Adv. Agron. 166, 1–129.

McLellan, E.L., Cassman, K.G., Eagle, A.J., Woodbury, P.B., Sela, S., Tonitto, C., Marjerison, R.D., van Es, H.M., 2018. The nitrogen balancing act: tracking the environmental performance of food production. Bioscience 68, 194–203.

Meenakshi, J.V., Johnson, N.L., Manyong, V.M., DeGroote, H., Javelosa, J., Yanggen, D. R., Naher, F., Gonzalez, C., García, J., Meng, E., 2010. How cost-effective is biofortification in combating micronutrient malnutrition? An ex ante assessment. World Development 38, 64–75.

Mehrabi, Z., McDowell, M.J., Ricciardi, V., Levers, C., Martinez, J.D., Mehrabi, N., Wittman, H., Ramankutty, N., Jarvis, A., 2020. The global divide in data-driven farming. Nat. Sustain. https://doi.org/10.1038/s41893-020-00631-0.

Mengutay, M., Ceylan, Y., Kutman, U.B., Cakmak, I., 2013. Adequate magnesium nutrition mitigates adverse effects of heat stress on maize and wheat. Plant Soil 368, 57–72.

Mulders, P.J., van den Heuvel, E.R., van den Borne, J., van de Molengraft, R., Heemels, W., Reidsma, P., 2021. Data science at farm level: explaining and predicting within-farm variability in potato growth and yield. Eur. J. Agron. 123, 126220.

Muscat, A., Olde, E.M. de, Ripoll-Bosch, R., van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., van Ittersum, M.K., Boer, I.J.M. de, 2021. Principles, drivers and opportunities of a circular bioeconomy. Nature Food 2, 561–566.

Nottingham, A.T., Meir, P., Velasquez, E., Turner, B.L., 2020. Soil carbon loss by experimental warming in a tropical forest. Nature 584, 234–237.

Paas, W., Accatino, F., Bijttebier, J., Black, J.E., Gavrilescu, C., Krupin, V., Manevska-Tasevska, G., Ollendorf, F., Peneva, M., San Martin, C., Zinnanti, C., Appel, F., Courtney, P., Severini, S., Soriano, B., Vigani, M., Zawalińska, K., van Ittersum, M.K., Meuwissen, M.P., Reidsma, P., 2021. Participatory assessment of critical thresholds for resilient and sustainable European farming systems. J. Rural Stud. 88, 214–226.

Parviainen, T., Helenius, J., 2020. Trade imports increasingly contribute to plant nutrient inputs: case of the Finnish food system 1996–2014. Sustainability 12, 702.

Pingali, P.L., 2012. Green revolution: impacts, limits, and the path ahead. Proc. Natl. Acad. Sci. U. S. A 109, 12302–12308.

Pingali, P., Mittra, B., Rahman, A., 2017. The bumpy road from food to nutrition security – slow evolution of India's food policy. Global Food Secur. 15, 77–84.
Poole, N., Donovan, J., Erenstein, O., 2020. Agri-nutrition Research: Revisiting the Contribution of Maize and Wheat to Human Nutrition and Health. Food Policy, 101976.
Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2018. Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted Research, United Kingdom. Global Change Biol. 24, 2563–2584.
Quan, Z., Zhang, X., Fang, Y., Davidson, E.A., 2021. Different quantification approaches for nitrogen use efficiency lead to divergent estimates with varying advantages. Nature Food 2, 241–245.
Quemada, M., Lassaletta, L., Jensen, L.S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S.K., Oenema, J., Richards, K.G., Oenema, O., 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agric. Syst. 177, 102689.
Reeves, P.G., Chaney, R.L., 2008. Bioavailability as an issue in risk assessment and management of food cadmium: a review. Sci. Total Environ. 398, 13–19.
Rinot, O., Levy, G.J., Steinberger, Y., Svoray, T., Eshel, G., 2019. Soil health assessment: a critical review of current methodologies and a proposed new approach. Sci. Total Environ. 648, 1484–1491.
Rosanoff, A., Kumssa, D.B., 2020. Impact of rising body weight and cereal grain food processing on human magnesium nutrition. Plant Soil 457, 5–23.
Rouphael, Y., Colla, G., 2020. Editorial: biostimulants in agriculture. Front. Plant Sci. 11, 40.
Rouwenhorst, K.H., van der Ham, A.G., Mul, G., Kersten, S.R., 2019. Islanded ammonia power systems: technology review & conceptual process design. Renew. Sustain. Energy Rev. 114, 109339.
Sarwar, M., Saleem, M.F., Ullah, N., Ali, S., Rizwan, M., Shahid, M.R., Alyemeni, M.N., Alamri, S.A., Ahmad, P., 2019. Role of mineral nutrition in alleviation of heat stress in cotton plants grown in glasshouse and field conditions. Sci. Rep. 9, 13022.
Silva, J.V., van Ittersum, M.K., Berge, H.F. ten, Spätjens, L., Tenreiro, T.R., Anten, N.P., Reidsma, P., 2021. Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: an appraisal of big data from commercial farms. Field Crop. Res. 269, 108176.
Singh, B.R., Timsina, Y.N., Lind, O.C., Cagno, S., Janssens, K., 2018. Zinc and iron concentration as affected by nitrogen fertilization and their localization in wheat grain. Front. Plant Sci. 9, 307.
Smith, M.J., 2020. Getting value from artificial intelligence in agriculture. Anim. Prod. Sci. 60, 46.
Soares, J.C., Santos, C.S., Carvalho, S.M.P., Pintado, M.M., Vasconcelos, M.W., 2019. Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. Plant Soil 443, 1–26.
Spohn, M., 2020. Increasing the organic carbon stocks in mineral soils sequesters large amounts of phosphorus. Global Change Biol. 26, 4169–4177.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347, 1259855.
Stevenson, J.R., Villoria, N., Byerlee, D., Kelley, T., Maredia, M., 2013. Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proc. Natl. Acad. Sci. Unit. States Am. 110, 8363–8368.
Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., 1993. Calculating soil nutrient balances in Africa at different scales. 1.Supra-national scale. Fert. Res. 35, 227–235.
Sun, H., Weaver, C.M., 2020. Rise in potassium deficiency in the US population linked to agriculture practices and dietary potassium deficits. J. Agric. Food Chem. 68, 11121–11127.
Sun, Z., Scherer, L., Tukker, A., Behrens, P., 2020. Linking global crop and livestock consumption to local production hotspots. Global Food Secur. 25, 100323.
Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizetti, B., Vries, W. de, van Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., 2012. Our Nutrient World: the Challenge to Produce More Food and Energy with Less Pollution. https://www.unenvironment.org/resources/report/our-nutrient-world-challenge-produce-more-food-and-energy-less-pollution.
Tenorio, F.A., McLellan, E.L., Eagle, A.J., Cassman, K.G., Andersen, D., Krausnick, M., Oaklund, R., Thorburn, J., Grassini, P., 2020. Benchmarking impact of nitrogen inputs on grain yield and environmental performance of producer fields in the western US Corn Belt. Agric. Ecosyst. Environ. 294, 106865.
Thornton, P.K., Herrero, M., 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nat. Clim. Change 5, 830–836.
Tuninetti, M., Ridolfi, L., Laio, F., 2020. Ever-increasing agricultural land and water productivity: a global multi-crop analysis. Environ. Res. Lett. 15, 0940a2.
Uwizeye, A., Boer, I.J.M. de, Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T.P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. Nature Food 1, 437–446.
van der Hoek, J., Duijff, R., Reinstra, O., 2018. Nitrogen recovery from wastewater: possibilities, competition with other resources, and adaptation pathways. Sustainability 10, 4605.
van der Kooij, S., van Vliet, B.J., Stomph, T.J., Sutton, N.B., Anten, N.P., Hoffland, E., 2020. Phosphorus recovered from human excreta: a socio-ecological-technical approach to phosphorus recycling. Resour. Conserv. Recycl. 157, 104744.
van Groenigen, J.W., van Kessel, C., Hungate, B.A., Oenema, O., Powlson, D.S., van Groenigen, K.J., 2017. Sequestering soil organic carbon: a nitrogen dilemma. Environ. Sci. Technol. 51, 4738–4739.
van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., Groot, H. de, Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? Proc. Natl. Acad. Sci. Unit. States Am. 113, 14964–14969.
van Loon, M.P., Hijbeek, R., Berge, H.F.M. ten, Sy, V. de, Broeke, G.A. ten, Solomon, D., van Ittersum, M.K., 2019. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. Global Change Biol. 25, 3720–3730.
van Zanten, H.H., van Ittersum, M.K., Boer, I.J. de, 2019. The role of farm animals in a circular food system. Global Food Secur. 21, 18–22.
Vaneeckhaute, C., 2021. Integrating resource recovery process and watershed modelling to facilitate decision-making regarding bio-fertilizer production and application. npj Clean Water 4, 15.
Vanlauwe, B., Dobermann, A., 2020. Sustainable intensification of agriculture in sub-Saharan Africa: first things first. Front. Agr. Sci. Eng. 7, 376–382.
Vogel, H.-J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., Wiesmeier, M., Wollschläger, U., 2019. Quantitative evaluation of soil functions: potential and state. Front. Environ. Sci. 7.
Vollset, S.E., Goren, E., Yuan, C.-W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., Azhar, G.S., Castro, E., Chalek, J., Dolgert, A.J., Frank, T., Fukutaki, K., Hay, S.I., Lozano, R., Mokdad, A.H., Nandakumar, V., Pierce, M., Pletcher, M., Robalik, T., Steuben, K.M., Wunrow, H.Y., Zlavog, B.S., Murray, C.J.L., 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. Lancet. https://doi.org/10.1016/S0140-6736(20)30677-2.
Vries, W. de, Schulte-Uebbing, L., Kros, H., Voogd, J.C., Louwagie, G., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Sci. Total Environ. 786, 147283.
Walling, E., Vaneeckhaute, C., 2020. Greenhouse gas emissions from inorganic and organic fertilizer production and use: a review of emission factors and their variability. J. Environ. Manag. 276, 111211.
Wang, M., Zheng, Q., Shen, Q., Guo, S., 2013. The critical role of potassium in plant stress response. Int. J. Mol. Sci. 14, 7370–7390.
Waraich, E.A., Ahmad, R., Ashraf, M.Y., 2011. Role of mineral nutrition in alleviation of drought stress in plants. Aust. J. Crop. Sci. 5, 764.
Weissengruber, L., Möller, K., Puschenreiter, M., Friedel, J.K., 2018. Long-term soil accumulation of potentially toxic elements and selected organic pollutants through application of recycled phosphorus fertilizers for organic farming conditions. Nutrient Cycl. Agroecosyst. 110, 427–449.
Welch, R.M., Graham, R.D., Cakmak, I., 2013. Linking agricultural production practices to improving human nutrition and health, 13-15 November. In: Expert Paper Written for ICN2 Second International Conference on Nutrition Preparatory Technical Meeting. Rome, Italy. http://www.fao.org/3/a-as574e.pdf.
Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R., Sinclair, F., 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron. Sustain. Dev. 40, 40.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., Vries, W. de, Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492.
Xu, X., He, P., Pampolino, M.F., Qiu, S., Zhao, S., Zhou, W., 2019. Spatial variation of yield response and fertilizer requirements on regional scale for irrigated rice in China. Sci. Rep. 9, 3589.
Yuan, S., Linquist, B.A., Wilson, L.T., Cassman, K.G., Stuart, A.M., Pede, V., Miro, B., Saito, K., Agustiani, N., Aristya, V.E., Krisnadi, L.Y., Zanon, A.J., Heinemann, A.B., Carracelas, G., Subash, N., Brahmanand, P.S., Li, T., Peng, S., Grassini, P., 2021. Sustainable intensification for a larger global rice bowl. Nat. Commun. 12, 7163.
Zhang, X., 2017. A plan for efficient use of nitrogen fertilizers. Nature 543, 322–323.
Zhang, X., Chabot, D., Sultan, Y., Monreal, C., DeRosa, M.C., 2013. Target-molecule-triggered rupture of aptamer-encapsulated polyelectrolyte microcapsules. ACS Appl. Mater. Interfaces 5, 5500–5507.
Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51–59.
Zhang, X., Davidson, E.A., Zou, T., Lassaletta, L., Quan, Z., Li, T., Zhang, W., 2020. Quantifying nutrient budgets for sustainable nutrient management. Global Biogeochem 34. Cycles.
Zhang, W., Zhang, W., Wang, X., Liu, D., Zou, C., Chen, X., 2021a. Quantitative evaluation of the grain zinc in cereal crops caused by phosphorus fertilization. A meta-analysis. Agron. Sustain. Dev. 41.
Zhang, X., Zou, T., Lassaletta, L., Mueller, N.D., Tubiello, F.N., Lisk, M.D., Lu, C., Conant, R.T., Dorich, C.D., Gerber, J., Tian, H., Bruulsema, T., Maaz, T.M., Nishina, K., Bodirsky, B.L., Popp, A., Bouwman, L., Beusen, A., Chang, J., Havlík, P., Leclère, D., Canadell, J.G., Jackson, R.B., Heffer, P., Wanner, N., Zhang, W., Davidson, E.A., 2021b. Quantification of global and national nitrogen budgets for crop production. Nature Food 2, 529–540.
Zoroddu, M.A., Aaseth, J., Crisponi, G., Medici, S., Peana, M., Nurchi, V.M., 2019. The essential metals for humans: a brief overview. J. Inorg. Biochem. 195, 120–129.