03

Transforming food systems: implications for phosphorus

Lead authors: Dana Cordell, Tim G. Benton
Co-authors: Paul J.A. Withers, Penny J. Johnes, Tina-Simone Neset, Bryan M. Spears

Left: A woman sells fruits and vegetables at Siti Khatijah Market, Kelantan, Malaysia. 'Phosphorus security' envisages a world where all farmers have access to sufficient phosphorus to grow enough food to feed a growing population a healthy diet while ensuring farmer livelihoods and minimising detrimental environmental and social impacts. Photograph taken by Alex Hudson on www.unsplash.com - www.unsplash.com/@aliffhassan91

Managing phosphorus underpins the sustainability of the food system and is vital in achieving future food security. Strategies to deliver phosphorus sustainability include a transition to circular phosphorus value chains, land-use planning approaches that support greater phosphorus use efficiency and a reduction in consumption of animal products. Affordable access to sustainable phosphorus sources is imperative to ensure food provision for all and to protect the livelihoods of smallholder and marginal farmers.

Suggested citation for this chapter: D. Cordell, T.G. Benton, P.J.A. Withers, P.J. Johnes, T.S. Neset, B.M. Spears. (2022) Chapter 3. Transforming food systems: implications for phosphorus, in: W.J. Brownlie, M.A. Sutton, K.V. Heal, D.S. Reay, B.M. Spears (eds.), Our Phosphorus Future. UK Centre for Ecology & Hydrology, Edinburgh. doi: 10.13140/RG.2.2.10598.91201

Challenge 3.1: Business as usual is unsustainable: we must produce healthier foods, using appropriate phosphorus inputs

Our food system is a significant cause of nutrient pollution in terrestrial, freshwater and marine ecosystems, and of global climate change, while more than half the global population are acutely hungry, malnourished, overweight, or obese. The public health and ecological costs of the current food system exceeds the economic value of agriculture. Systemic transformation is required for food systems to become environmentally sustainable and provide nutritional security for all. Sustainable phosphorus strategies must directly support, not hinder, this transformation. On the current path, the global food system will increase the mining of finite phosphate rock to produce fertiliser, feed additives and food supplements, and is not tracking towards a circular phosphorus system (driven on recycled phosphorus inputs).

Challenge 3.2: Increasing global consumption of animal products is increasing phosphorus demand

The amount of phosphorus required to produce the average per capita global diet has increased by 38% in the last 50 years, due to the rise in consumption of animal products, increase in average per capita consumption and increased food waste. Excluding phosphorus-efficient grass-based systems, a large proportion of cropland is needed to support intensive meat and dairy production through concentrated animal feeding operations. This trend is driving increased mining of phosphate rock for fertilisers, animal feed and supplements. Unhealthy diets, including overconsumption of animal products, are also a significant contributor to non-communicable diseases.

Challenge 3.3: Balancing intensive agriculture with low input farming

Agricultural intensification increases productivity yet increasing phosphorus inputs to crops can also over-enrich adjacent land and waterbodies with nutrients. Lowering phosphorus inputs reduces environmental risk and promotes biodiversity but may restrict yield in the long-term. Strategies need to provide the right balance of intensification to avoid the need to convert more land to agriculture. Optimising the multitude of costs and benefits and taking account of direct and indirect impacts can be challenging and context specific. The challenge we face is in developing low phosphorus input farming systems which can sustain food production.

Challenge 3.4: Many farmers lack access to phosphorus, threatening their livelihoods

Currently, 1 in 7 farmers cannot access or afford phosphorus fertilisers to increase productivity, reducing their ability to maintain food security and livelihoods. Those farmers most affected are rural smallholder farming families, particularly in less economically developed countries, but also in some more economically developed countries. There are marked global inequalities in access to phosphorus as a resource, leading to substantial inequalities in the distribution of risks to food security.

Solution 3.1: Managing phosphorus sustainably can support a shift to healthier diets

Global food systems must produce, actively support, and provide access to nutritious food and diets for all. This shift, from 'market-led' to 'sustainable' food security, can reduce phosphorus demand and adverse impacts on ecosystems and society. Concurrently, strategies to deliver better phosphorus sustainability, including circular phosphorus value chains, can benefit agricultural economies, whilst effective monitoring systems, data sharing, and knowledge exchange can ensure strategies adapt to a transforming food system.

Solution 3.2: Shift global consumption of animal products towards plant-based diets

Reduced consumption of animal products especially from intensive production systems in some regions may reduce global agricultural phosphorus demand and contribute to healthier environments. Increased awareness amongst policymakers and the public of the environmental impacts of phosphorus use in food production, and the human health risks of excessive consumption of animal products, will be an essential driver of change. Knowledge exchange between academics, stakeholders and the public can help identify solutions to support a transition to more phosphorus sustainable consumer behaviour, as could policy and regulatory changes (including internalising the environmental costs into food pricing).

Solution 3.3: Integrated landscape strategies to improve phosphorus use efficiency and reduce losses

There is an opportunity to develop novel land-use planning approaches to support more sustainable phosphorus use across multiple and interacting contexts. These include agricultural production, ecosystem and human health, local economies and regional capacity for institutional planning and coordination. Sustainable farming systems in which animal and crop production are more integrated and animal residues and manures are treated as valuable phosphorus resources, will support efforts to increase phosphorus use efficiency within landscapes while reducing negative impacts on aquatic and terrestrial ecosystems.

Solution 3.4: Better support for smallholder farmers

Affordable access to sustainable phosphorus sources is imperative to ensure food provision for all and to protect the livelihoods of smallholder and marginal farmers. Multiple options exist to help improve phosphorus access in these communities. These include access to credit, extension services, investment in sustainable infrastructure (such as local phosphorus recycling systems from food waste and sanitation where available), and knowledge exchange to support better phosphorus use efficiency and recycling. Developing the capacity to recycle phosphorus from local and regional food systems where available can help to shift reliance away from mineral phosphorus fertilisers.

3.1 Introduction

All farmers need access to phosphorus (P) to grow crops, regardless of what they grow or where they farm. Yet, access to affordable and sustainable sources of P is, currently, not guaranteed. At the same time, excess P use can harm aquatic ecosystems and in turn the food, ecosystem and agricultural services they support (see Chapter 5). Managing P sustainably, therefore, underpins the sustainability of the food system and is vital in achieving future food security. To make progress towards a sustainable global food system we must take a multiple-stressor mitigation approach. This includes better managing P use in addition to other essential macro- and micro-nutrient sources essential to food production to reduce the impact of food production on climate change, human and ecosystem health, and to addresses inequalities in access to nutritious food from local to global scales. Efforts focused on single-stressor action are not sustainable and will be unlikely to tackle the scale of the challenge. Multiple United Nations Sustainable Development Goals (SDGs) demand a transformation to more sustainable food systems, however, the role of P management in food systems is not yet sufficiently addressed. 'Phosphorus security' envisages a world where all farmers have access to sufficient P to grow enough food to feed a growing population a healthy diet while ensuring farmer livelihoods and minimising detrimental environmental and social impacts (Cordell, 2010).

Actions to improve global P security should be underpinned by a comprehensive understanding of food systems and the flows of P within them. Such actions should be co-developed with relevant stakeholders to achieve food security whilst delivering multiple benefits to society, for example as defined by the SDGs. This will decrease the likelihood of 'lock-ins', where actors are unwilling or unable to exit a position because of sunk infrastructure costs, regulations, or penalties. For example, while phosphorus recovery will be essential, investing in expensive phosphorus recovery technologies that do not produce phosphorus in biochemical forms that can be easily used to produce fertilisers, and are more energy-intensive to produce than mineral fertilisers, may not be the best use of financial resources.

One significant challenge to overcome with respect to the global food system is the equitable supply of, and access to, phosphorus. Only a few countries control the bulk of non-renewable phosphate reserves and production, due to natural geological phosphate formations. Most countries are import-dependent and hence vulnerable to price shocks, supply disruptions, and import barriers (see Chapter 2), which can disrupt food security and farmer livelihoods if not sufficiently managed.

In this chapter we provide an overview of the importance of sustainable P management in global food security, outlining the need to transform our food system to enhance public health and farmer livelihoods whilst reducing adverse impacts on the environment. We then propose possible future scenarios for food systems and highlight that whilst the future trajectory of food system transformations remains uncertain, it should embrace both trade-offs and synergies for P security. We then summarise some of the key challenges and solutions to achieving P security within a food system under transformation.

3.1.1 Food and fertiliser price spikes

Food and fertiliser prices have a significant impact on food systems, especially in developing economies. In 2007–2008, the nominal prices of almost all food commodities increased by more than 50%, then dropped soon after, and surged again in 2010–2012 (FAO, 2017). This was accompanied by an 800% increase in the price of phosphate rock in 2008, with a further peak in 2011–2012, impacting P fertiliser prices and food security (de Ridder et al., 2012) (Figure 3.1).

Against the background of declining food prices since the 1950s (Jacks, 2018), the 2007–2008 increase in the FAO Food Price Index came as a global surprise. It was likely driven by a combination of increasing biofuel demand, speculation in commodity futures markets, countries' aggressive food stockpiling policies, trade restrictions, macroeconomic shocks to the money supply, exchange rates, and economic growth (Tadasse et al., 2014). Whilst the 2008 phosphate rock (PR) price spike is connected, the drivers are again complex, contentiously debated, and likely include a combination of market supply and demand dynamics for agricultural products, instability in energy prices and geopolitical control on exports (Childers et al., 2011; Cordell et al., 2015; IFA, 2011; Khabarov and Obersteiner, 2017) (see Chapter 2).

Spikes in food and fertiliser prices directly affected access to food for the global poor and vulnerable. The risk of food production being unable to meet the rapidly growing global population demand for food (and the water and energy needed to supply it), as well as the impacts of climate change, was cause for global concern, placing P sustainability on the global food security agenda.

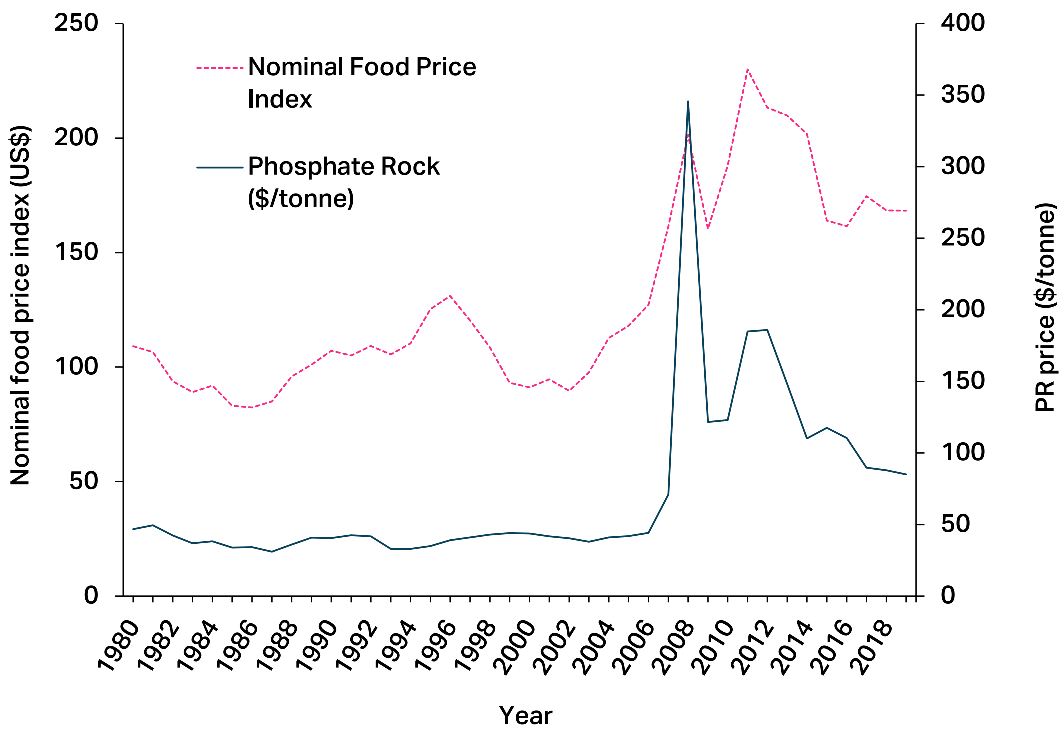


Figure 3.1 FAO food price index (international prices of a basket of food commodities) in nominal terms (data source: FAOstat) and phosphate rock price (US$/t) (Data source: World Bank Commodity Price data) from 1980 to 2019, showing peaks in price between 2007-2008, and again in 2011.

3.1.2 Shifting paradigms of food security

Food security occurs, according to the FAO definition, when "all people, all of the time, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2009). This definition is often discussed under a conceptual framework of supply availability and access (including economic access through price), the ability to utilise food (e.g. safe preparation) and stability (i.e. without undue fluctuations in availability and access).

Historically, discussions about food security have focussed on the provision of sufficient food (with emphasis on staple crops supplying calories) for the global poor, particularly in the developing world. More recently this discussion has been nuanced by recognition of two further key issues (Figure 3.2). First, is the need to address the global rise in obesity and the health burden this creates through non-communicable diseases (NCD Risk Factor Collaboration (NCD-RisC), 2016). In many parts of the developed world, obesity is related to inequality and dietary choice and driven by the availability of calorie-dense food that is relatively cheap, whereas nutritionally dense food is expensive (Darmon and Drewnowski, 2015). Poor education around healthy food choices, but perhaps most importantly poor food environments coupled with effective marketing strategies of 'junk food' companies, contribute to this issue. There is an increasing need to focus on providing diets that are healthy and not obesogenic, going beyond providing calories to providing nutrition (Swinburn et al., 2019).

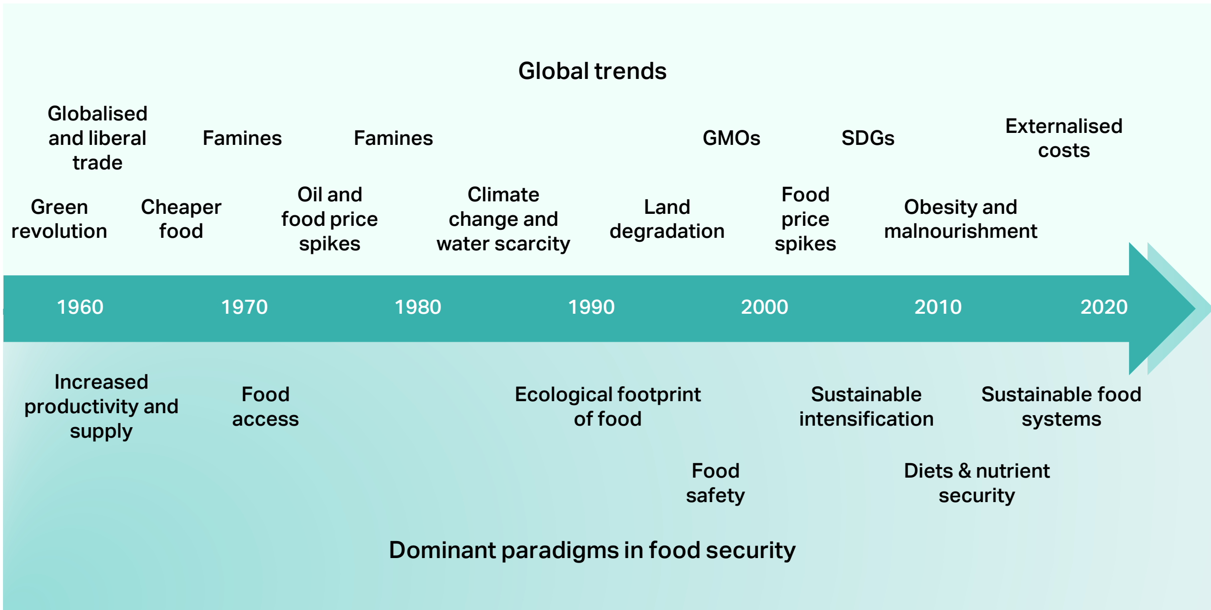


Figure 3.2 Global drivers that have informed discourse on food security since the 1960s to present (GMO – genetically modified organisms; SDGs – sustainable development goals).

Second, is the need to build environmental sustainability into food production systems. Following the 2007–2008 food price spike, and recognising the growing demand for food driven by a rising, more affluent population, projections of demand for food (based on historical trends) suggested a 70–100% demand increase by 2050 (Alexandratos and Bruinsma, 2012). These projections launched a discussion about how to meet that demand by raising the output per unit area (i.e. agricultural intensification) but doing it sustainably. This concept is called sustainable intensification and can be described as a process or system where agricultural yields are increased – or maintained – whilst reducing the environmental impact and without the conversion of additional non-agricultural land (Baulcombe et al., 2009; Benton, 2016; Pretty et al., 2011). Garnett et al. (2013) highlighted that whilst sustainable intensification is an evolving concept, it is only part of what is needed to improve food system sustainability and is not synonymous with food security. Food security has multiple social, ethical and environmental dimensions and to achieve it requires more than just changes in agricultural production. It is also the case that a move to 'sustainable intensification' of food production against rising demand is unlikely to be achieved without increasing environmental impact, albeit at a slower rate than might occur if such approaches were not adopted.

The 2015 Paris Agreement reflected a consensus on the existence of "planetary boundaries", setting limits on global temperature increase related to greenhouse gas (GHG) emissions (IPCC, 2018) and informing discussions on the role of the global food system as a key driver of global climate change, as well as the impact of climate change on food security. This has led to the recognition that "supply-side" measures alone will not deliver sufficient increases in sustainability within food systems (Bajželj et al., 2014; Springmann et al., 2018). For example, redressing the increasing consumption of meat and dairy products in both developed and developing economies may be necessary (Hoekstra, 2012; Leip et al., 2015; Poore and Nemecek, 2018; Röös et al., 2018). In 2021, the term 'Food Systems' was officially adopted at a summit convened by the United Nations to better integrate these issues within the delivery frameworks of the SDGs (United Nations, 2021).

3.1.3 Why the food system needs to change

With more people suffering from hunger and malnutrition than consuming healthy diets (FAO, IFAD, UNICEF, WFP, and WHO, 2017; FAO et al., 2018), the need for transformation of the food system is primarily driven by the need to address malnourishment. This runs alongside the need to reduce the adverse impacts of food production on the global climate system and ecosystem health across all planetary domains. However, transforming the food system to deliver healthy and sustainable diets also addresses P sustainability and climate security (Willett et al., 2019). There is growing recognition that a systemic transformation of the food system is required, and that "business as usual is not an option" (Webb et al., 2020). This recognition comes not just from academic institutions (Fears et al., 2019; Poore and Nemecek, 2018; Ripple et al., 2017) and the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018) but also from the business community (High Level Forum, 2019; World Economic Forum, 2017). Furthermore, environmental and civil society institutions, including the World Wide Fund for Nature Fund (WWF) (SustainAbility and WWF, 2018) and the World Resources Institute (WRI) (Searchinger et al., 2019) acknowledge the need for change. However, if "business as usual is not an option" what will the future look like for our food systems, and how will this relate to P security?

3.2 Plausible food system scenarios

In the following, we propose a suite of plausible future scenarios for food systems (Benton, 2019). Scenarios are a route to aid decision-making under conditions of high uncertainty (Courtney et al., 1997; Rosa et al., 2017), when past trends cannot necessarily be extrapolated into the future with confidence, and where the future is likely to be shaped by drivers or events which may plausibly lead to very different outcomes. Whilst scenarios may take a variety of forms, a common approach is to identify the two most important drivers which will shape the future, but for which there is great uncertainty about what form they will take (e.g. World Economic Forum, 2017).

A variety of recent exercises have suggested two axes, defining four plausible scenarios (see Benton, 2019 for an overview). These axes are:

Axis 1: Dietary shifts from today's diet, towards food systems that provide healthy food with low-externalised costs to human health and the environment.

The drivers for such a shift include climate change mitigation, health care costs of malnutrition and associated non-communicable diseases, the rise of anti-microbial resistance from intensive livestock production (Rushton, 2015), air quality impacts caused by intensive agriculture and volatilisation of nitrogenous fertiliser (Sutton et al., 2013), the rise in plastic and food waste, and demand to reduce nutrient and pesticide use in agriculture (Chapter 5). Other initiatives that support a shift to healthy and/or sustainable diets include the EAT-Lancet Commission (Willett et al., 2019), Agrimonde foresight work on food security and land use (Paillard et al., 2014), the EU JRC's food systems' foresight study (Bock et al., 2014) and Shared Socio-economic Pathway (SSP) SSP1 for the IPCC (O'Neill et al., 2017).

Axis 2: Change in globalisation towards regional or local food systems.

The dominant view has been that global trade based on economies of scale and comparative advantage is an economic necessity. However, geopolitical trends over the last five years, such as the erosion of the post-WW2 architecture of international cooperation and the rise of inward-looking and protectionist policies driven by increasing global inequality and migration, suggest the future may be shifting towards less globalised trading systems, compared to the trend of the last 70 years. A shortening of supply chains may also be driven by climate change impacts on current food systems and geopolitical instability, incentivising local sourcing to reduce reliance on imported foods. Social change, for example, increasing trust in locally produced foods to support local businesses and communities, might also drive reform (Moberg et al., 2021).

Unforeseen shocks like COVID-19 can also act to increase the resilience of local food systems, or at least highlight the fragility of long supply chains (FAO, 2020). Other exercises also considering the global to local dimension include the EU JRC's food safety foresight study (Mylona et al., 2016), and its scoping study (European Commission, 2013) as well as the IPCC's SSPs (e.g. SSP3 considers more regionalised economies). Both the USA and UK governments publish periodic reports by their intelligence communities, which, in the most recent editions, have highlighted food security scenarios, including the impacts of radical change to the international architecture of trade and cooperation (The National Intelligence Council (USA), 2017; UK Ministry of Defence, 2018). The Millennium Ecosystem Assessment scenarios (Carpenter et al., 2005) also contained a global-to-regional axis. Other discussions around the balance of risks, benefits and costs of trade have included the UK's Climate Change Risk Assessment (Challinor et al., 2018) and the EU JRC's 2030 Foresight Report on Food (Maggio et al., 2015).

Acknowledging the uncertainty associated with these factors, we can define four plausible, alternative, scenarios for food systems, each of which has implications for P, with respect to what food is grown, where it is grown, and how it is grown (Figure 3.3 and Table 3.1).

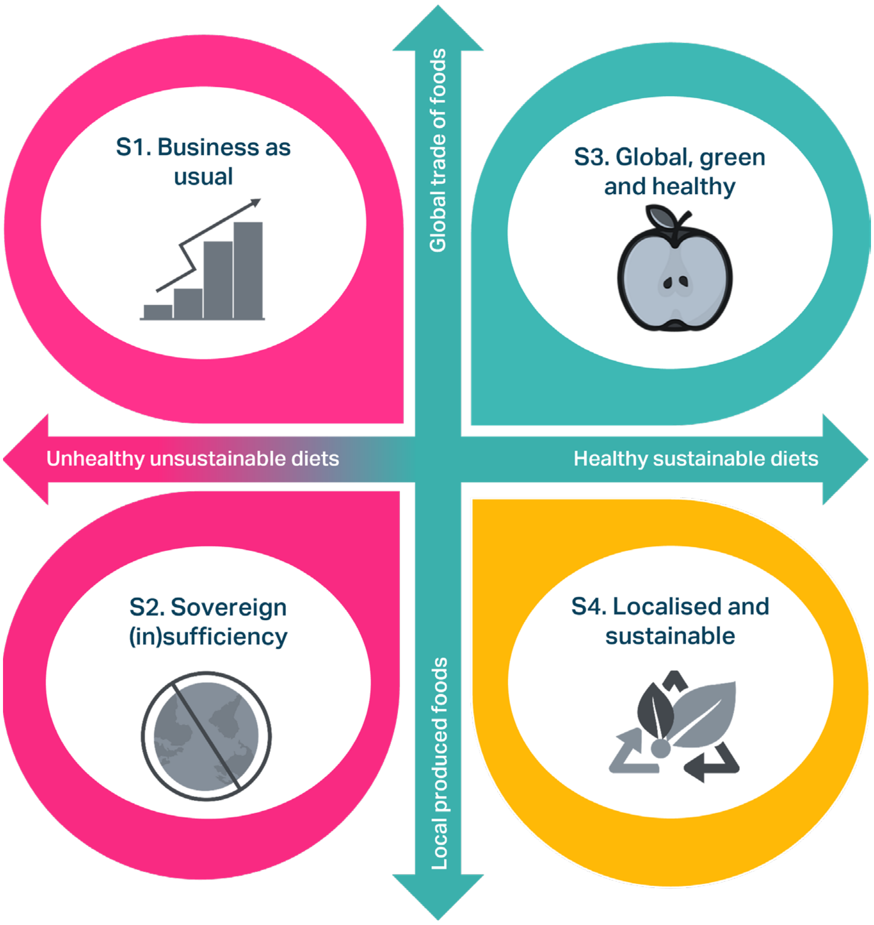


Figure 3.3 Four plausible, alternative, scenarios for food systems, based on axes of global-local connectivity, and degree of dietary shifts. Source: Benton (2019) and World Economic Forum (2017).

Table 3.1 Scenario descriptions of four plausible, alternative, scenarios for food systems, based on axes of global-local connectivity, and degree of dietary shifts Source: Benton (2019) and World Economic Forum (2017).

Scenario	Scenario description
Scenario 1 (S1): Business as usual Unchecked consumption in a globalised world.	Increasing consumption of processed foods based on a few commodity crops. Livestock production continues to increase but is increasingly dependent on grain. Wasting food and over-consuming calorie-dense food continues to be economically rational. Obesity and related ill health and environmental damage increase. "Sustainable intensification" dominates agriculture because meeting demand is the priority. Impacts of the food system exacerbate climate change, nutrient pollution, and biodiversity loss. Land required for climate change mitigation measures (e.g. afforestation, biofuels) adds to land competition. High-tech, intensive cropping systems and intensive livestock production dominate. Economies of scale drive farm amalgamation into bigger units, further marginalising smallholders.
Scenario 1(S2): Sovereign insufficiency Significant reduction in global trade with no change in diets.	Global distrust in international cooperation. Diets are increasingly based on nationally available crops. Diversity of diets shrinks compromising human health, driven by increased reliance on processed food. As the comparative advantage of globally traded food is lost, most countries need to significantly intensify agriculture to become more self-sufficient, leading to increased use of inputs like fertilisers and pesticides. Impacts of the food system exacerbate climate change, nutrient pollution, and biodiversity loss. Endowment-poor, high population countries project more power to ensure food security (e.g. land grabbing). Endowment-poor, low population nations struggle leading to increased human migration. The last two points undermine the national security of endowment-rich countries.

Scenario 3 (S3): Global, green, and healthy Globalised supply chains coupled with a switch towards more "sustainable" and healthy diets	People eat less, aiming for the right amount of calories and with lab meat dominating the alternative protein market. They also produce less waste. Commodity-crop agriculture dominates; nutrition is added through food and agronomic biofortification. Food is processed but with fewer sugar and fats than in Scenario 1. Intensification occurs to meet rising demand but is increasingly focussed in "breadbaskets" of commodity production where there is both scale and intensity of production. "Sustainable intensification" through increasing efficiency is the main focus of environmental concerns. Climate change mitigation actions reduce the need for land-based negative emissions measures, decreasing competition for land. Governments incentivise lower waste through subsidies, food pricing, and waste and food-carbon taxes. Small-scale intensive horticulture increases delivering high-value nutritious crops more widely (especially peri-urban and vertical farming). Adoption of large-scale horticulture by technologically advanced, arid, countries using technological solutions to provide water.
Scenario 4 (S4): Localised and sustainable Circular food systems are diversified to provide healthy diets in a closed system.	Agriculture is local/regional, diverse, with complex rotations, mixed farming, and nutrient recycling. This is necessary to produce nutritionally diverse diets for the population. Without global competition, efficiency should be built into food systems, because local systems struggle to produce an excess of food. People eat less, aiming for a healthy diet that is sustainably produced. Rather than eat hyper-processed foods, people switch to whole foods cooked at home because food is more expensive. Agricultural policy is driven by nutritional needs and environmental protection, not just economic growth. Health costs are avoided because people eat healthily, and, along with circularity, agriculture is more diversified and landscapes more heterogeneous. Nutrient losses are reduced leading to environmental recovery and a reduction in greenhouse gas emissions from land-based food systems alleviates impacts on climate change. Localised systems will exacerbate among-country inequality, which may lead to aggressive land-grabbing (as with Scenario 2). Localised food systems experience low resilience to local extreme weather events, but are not exposed to risks from interrupted trade (which may become more common as climate impacts increase). Food systems reflect local conditions, creating diet seasonality and locally adapted produce.

The scenarios describe plausible future food systems and define different research and policy agendas. We stress that scenarios do not describe the "most likely future"; their main value lies in providing stress tests to aid in future policy development. However, these scenarios do suggest the future farming system – and the associated needs for, and impacts on, P – may not reflect a linear extrapolation of current farming systems. Therefore, farming systems should avoid being locked into an undesirable future (e.g. creating a greater reliance on fewer crops when the future may require diversification), but instead, be designed to be adaptive. Table 3.2 (presented at the start of the Solutions section in this chapter) identifies the implications for P, of sustainable transformations of the food system.

3.2.1 Implications for farming and the food system of a transition to healthy diets

Currently, about 2.5 times more cereals are grown worldwide than is needed to meet US dietary guidelines and only a fifth of fruit and vegetables needed are grown (KC et al., 2018). The EAT-Lancet report (2019) states that transformation to healthy diets by 2050 will require the average global consumption of fruits, vegetables, nuts and legumes to double, and consumption of foods such as red meat and sugar to be reduced by more than 50%. Currently, there is a stark global misalignment between what we eat and what we need for a healthy diet (EAT, 2019), though with regional variations (Figure 3.5 - see the following page spread). A move to a diet that supports a preventative health care system, therefore, has significant implications for agriculture, and consequently phosphorus.

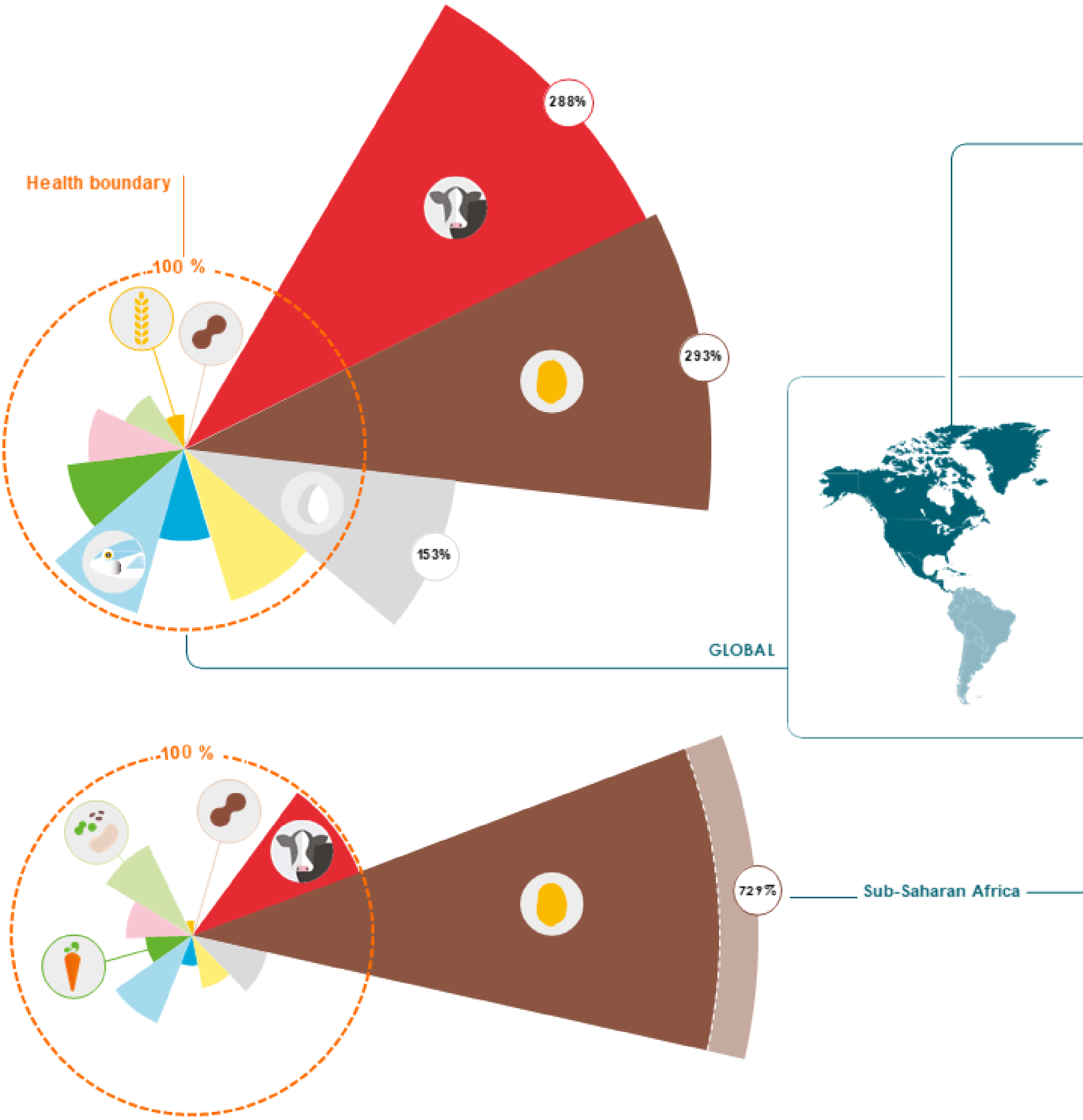
A sustainable food system implies more flexitarian diets (Machovina et al., 2015; Springmann et al., 2018). Globally, eating less meat, especially red meat, and animal products, is required to reduce the emission of GHG from the global food system, a significant step in mitigating climate change (IPCC, 2018). Life cycle analysis used to underpin this shift is based on CO_2 equivalent emissions per unit mass of meat (de Vries et al., 2015; McAuliffe et al., 2018a). However, replacing the 'mass' with 'nutrient content' of meat as the functional unit can dramatically alter relative emissions intensities associated with different livestock systems. In some cases, cattle systems can outperform pig and poultry systems (McAuliffe et al., 2018b).

Animal welfare can, and already does, influence societal dietary behaviours, which can have global impacts on agricultural systems, tending to drive a decrease in intensive livestock production and support more local food production with higher priorities for animal welfare. However, it is not clear if a reduction in meat consumption will lead to a compensatory increase in plant-based protein consumption. On average, globally, people consume too much animal protein (Figure 3.5), and protein in general (WRI, 2016). Thus, there may be little nutritional need to substitute the same quantity of animal protein with plant-based protein. A shift to more plant-based diets creates new challenges and opportunities for meeting the fresh fruit and vegetable demands of urban populations. The substitution of animal protein with insect protein in human diets warrants further investigation (Durst et al., 2010; Martin, 2014) (Figure 3.4), as does the use of insect protein as an alternative or supplementary source of animal feed (Leiber et al., 2015). What is clear is that our food systems are unpredictable and transforming, highlighting a significant challenge for future P management.

In the following section, we discuss the key challenges and solutions with respect to achieving more sustainable P use to deliver greater food security.

Figure 3.4 An 'Essento Insect Burger' contains 30% organic mealworms (Tenebrio molitor) farmed in Switzerland, along with chickpeas, bulgur, spelt, carrots, celery and a spice mix. The burgers, made by Swiss startup, Essento, are available (as of August 2021) in all larger Coop branches in Switzerland and for food service companies in Austria, Germany and Switzerland. Photograph copyright of Essento.

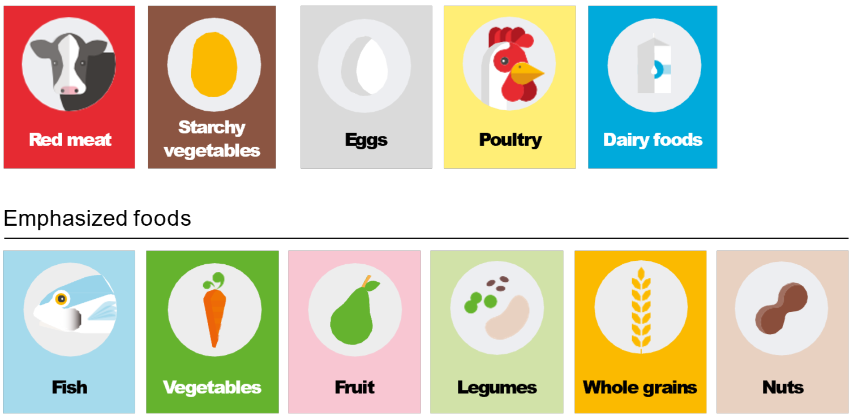
Figure 3.5 What we eat versus what we need for a healthy diet as the global average (left middle) and in North America, South Asia and Sub-Saharan Africa. A healthy diet is indicated by the dotted line orange circles (the health boundary). Food types that expand beyond the health boundary are eaten in excess, whilst more should be consumed of the food types that fall short of the health boundary. The figure shows that globally we consume far more red meat and starchy vegetables than required for a healthy diet, and far too few legumes, whole grains, fruit and vegetables. Source: adapted from (EAT, 2019). Reprinted from the EAT-Lancet Commission Summary Report, with permission from Elsevier.

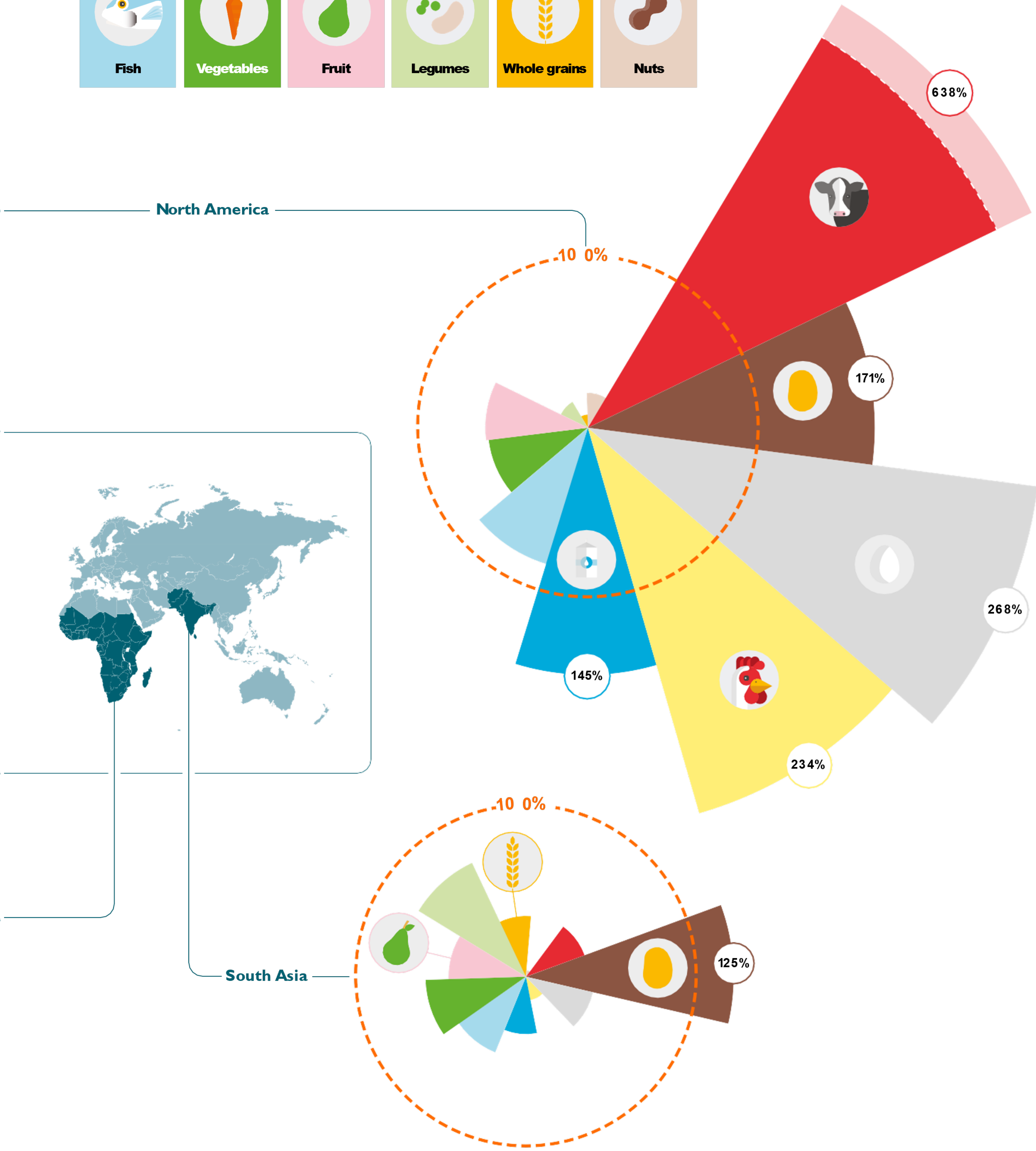


Limited intake

Optional foods

Emphasized foods





3.3 Challenges

Challenge 3.1: Business as usual is unsustainable: we must produce healthier foods, using appropriate phosphorus inputs

Our food system is a significant cause of nutrient pollution in terrestrial, freshwater and marine ecosystems, and of global climate change, while more than half the global population are acutely hungry, malnourished, overweight, or obese. The public health and ecological costs of the current food system exceeds the economic value of agriculture. Systemic transformation is required for food systems to become environmentally sustainable and provide nutritional security for all. Sustainable phosphorus strategies must directly support—not hinder—this transformation. On the current path, the global food system will increase the mining of finite phosphate rock to produce fertiliser, feed additives and food supplements, and is not tracking towards a circular phosphorus system (driven on recycled phosphorus inputs).

A systemic transformation of the food system is required. Under a 'business as usual' scenario, including current inefficient food production and consumption practices, it has been estimated that a 70-100% increase in crop production will be required to feed an expected global population of 9.7 billion in 2050 (based on 2005 levels) (Tilman et al., 2011). However, these estimates misinterpret underlying projections and ignore recent and potential production gains across the whole food value chain. Hunter et al., (2017) argue that an increase in production by 25-70% will be sufficient although simply intensifying current food systems to meet this demand is not sustainable. The current food system, including societal dietary choices, is widely acknowledged as eroding human and planetary health (IPCC, 2019; Willett et al., 2019).

Dietary-related malnourishment (including both under-nutrition and over-consumption of calories) is the prime global determinant of morbidity and is affecting every society in every country (Development Initiatives, 2018; GBD 2017 Risk Factors Collaborators, 2018). In 2016, 821 million people were acutely hungry, with an additional 2 billion undernourished. At the same time 2.3 billion people were overweight or obese (FAO, IFAD, UNICEF, WFP, and WHO, 2017; FAO et al., 2018). There are now more obese adults in the world than underweight and, if current trends continue, by 2025 there will be more severely obese adult females than underweight (NCD Risk Factor Collaboration (NCD-RisC), 2016). Simply put, out of every nine people, one person is starving, three people are undernourished, and three people are overweight or obese. In the developed world, at least, obesity is often linked to poor diets and poverty (Darmon and Drewnowski, 2015), because many cheaper foods are rich in calories but poor in nutrition. These foods are based on major commodity crops providing oil, sugar and starch (Development Initiatives, 2018). The ill-health burden that arises from malnourishment is also a growing economic burden (FAO, IFAD, UNICEF, WFP, and WHO, 2017; FAO et al., 2018). When combined with the environmental costs of producing foods (Burlingame et al., 2012; Kahiluoto et al., 2014; SustainAbility and WWF, 2018; West et al., 2014), including impacts of agricultural nutrient use, the cost of the current food system far exceeds its current economic value (Collins et al., 2018; Fitzpatrick et al., 2017; TEEB, 2018).

Food production practices must change to avoid further P-related environmental damage. For example, there is a need to reduce the inputs of non-renewable PR to produce food through increased nutrient recycling and more efficient utilisation of P in agricultural systems. The use of mineral fertilisers has played a crucial role in feeding billions of people over the past 60 years. Mining PR for use as fertiliser, and other human changes to the global P cycle, have increased the rate of P movement from mineral rock deposits to the ocean by four-fold (Falkowski et al., 2000; Smil, 2000). Phosphorus losses from land to surface waters have increased globally from around 5 to 9 Mt P year^{-1} over the 20th century (Beusen et al., 2016). Significant P losses are delivered from food production systems, such as livestock wastes or runoff from P-rich agricultural soils, or as excreted wastes, in the form of sewage discharges, into waterbodies with detrimental impacts on ecosystem and human health (see Chapter 5). Low P use efficiency (PUE) throughout food systems (from farm to fork and beyond) is widely acknowledged in Europe (Fischer et al., 2017; Muhammed et al., 2018; van Dijk et al., 2016), China (Lou et al., 2015), Brazil (Fischer et al., 2018; Withers et al., 2018) and the USA (Suh and Yee, 2011) (see Chapter 4). Low PUE drives losses that could be recouped to drive more sustainable food systems in these regions and others. More widespread adoption of strategies to increase PUE is urgently needed.

Challenge 3.2: Increasing global consumption of animal products is increasing phosphorus demand

The amount of phosphorus required to produce the average per capita global diet has increased by 38% in the last 50 years, due to the rise in consumption of animal products, increase in average per capita consumption and increased food waste. Excluding phosphorus-efficient grass-based systems, a large proportion of cropland is needed to support intensive meat and dairy production through concentrated animal feeding operations. This trend is driving increased mining of phosphate rock for fertilisers, animal feed and supplements. Unhealthy diets, including overconsumption of animal products, are also a significant contributor to non-communicable diseases.

Global consumption of animal products is rising, with a significant increase in countries such as Brazil and China, although at levels below those in industrialised countries (Westhoek et al., 2015).

The amount of P required to produce the average per capita global diet has increased by 38% in the last 50 years (Metson et al., 2012), due to the rise in consumption of animal products and increased food waste (and calorific intake in some regions). The current average per capita protein intake in the EU is about 70% higher than recommended (WHO, 2003). In Europe, ~20% of total P imported is for animal feed, whilst 60% of P in harvested crops is used in animal feed, and only ~30% is directly consumed by humans in plant-based food (van Dijk et al., 2016). In addition to grass-based systems, a large proportion of cropland is needed to support intensive meat production in concentrated animal feeding operations. Livestock density is, therefore, a major driver of the overall low PUE in national and regional food systems, both in grazed and in animal feed supplemented systems (e.g. Withers et al., 2020; Rothwell et al., 2020).

Global demand for P is highly influenced by diets that are high in animal protein (especially red meat) (Metson et al., 2012). For example, up to 16 times more P (and other resources) is required to produce a unit of beef from a concentrated animal feeding operation than to produce plant-based proteins (Metson et al., 2012). However, changing eating habits at the population scale is complex because behaviours are based on a large set of factors, unique to each person and their environment (see Chapter 8). Further, a third of all food produced globally is wasted (FAO, 2011), which contains P, resulting in a significant environmental and economic burden. For P, this means a significant unnecessary P demand and associated nutrient pollution (Kummu et al., 2012). We are currently on track for a more wasteful future scenario (i.e. 'unchecked consumption and sovereign (in) sufficiency') in which P demand will increase.

Challenge 3.3: Balancing intensive agriculture with low input farming

Agricultural intensification increases productivity yet increasing phosphorus inputs to crops can also over-enrich adjacent land and waterbodies with nutrients. Lowering phosphorus inputs reduces environmental risk and promotes biodiversity but may restrict yield in the long-term. Strategies need to provide the right balance of intensification to avoid the need to convert more land to agriculture. Optimising the multitude of costs and benefits and taking account of direct and indirect impacts can be challenging and context specific. The challenge we face is in developing low phosphorus input farming systems which can sustain food production.

Agricultural intensification using mineral P fertilisers, high-yielding crops, irrigation, and pesticides has contributed significantly to the large increases in food production over the past 60 years. Nevertheless, shortages of land that can be converted to agricultural use without inflicting yet greater damage on the environment (Lambin et al., 2013) mean there is still a need to increase the output of food, and other products like fibres, on existing agricultural land, unless there are dietary shifts that change demand. A similar scenario is emerging for aquaculture.

However, such intensification has long been known to alter the biological interactions and patterns of resource availability in ecosystems, with serious local, regional, and global environmental consequences (Matson et al., 1997). Some intensification of food production may well be necessary for sustainable human development, however, the increase in intensive agriculture has complex impacts on P demand and losses to waters (Ockenden et al., 2017). For example, while high-yield farming might increase PUE (Syers et al., 2008), increasing P use per hectare also increases the accumulation of unused P in the landscape both on land and in waters (Powers et al., 2016; Withers et al., 2014a). Historically in the global north, farmers have been advised to over-supply P to avoid risking yield loss (so-called insurance-based farming; Withers et al., 2014b), and areas with intensive livestock systems add further manure P loading pressures on the landscape, greatly exacerbating pollution risks to neighbouring water bodies (Leip et al., 2015; Powers et al., 2016; Withers et al., 2014b).

In some regions, such as the tropics, the need to increase food production is driving farming on 'P fixing' soils. Phosphorus readily binds to these soils, meaning a lower proportion of P applied as fertiliser is available for plants (Batjes, 2011; Sanchez et al., 2003). To overcome this, farmers often over-apply P well above plant requirements, increasing, over time, the risk of P transport to water bodies in runoff (Withers et al., 2018). Roy et al. (2016) estimate that intensification of the 8–12% of global croplands overlying P-fixing soils in 2005 would require 1–4 Mt P year^{-1} to overcome P fixation limits, equivalent to 8–25% of global inorganic P fertiliser application that year. This imposed P 'tax' is in addition to P added to soils and subsequently harvested in crops, and is projected to double to 2–7 Mt P year^{-1} for scenarios of cropland extent in 2050.

Continued high P inputs inevitably lead to high P losses from food systems (Doody et al., 2016; Withers et al., 2020). There is little evidence to date that this relationship can be effectively decoupled by best land management practices without transforming food systems. Nevertheless, PUE can be increased in some regional food systems by a range of measures. These include: reducing unnecessary P use in fertilisers and feeds; careful management of the P fertilisers and manures that are applied; breeding more P-efficient crop cultivars and novel and more precise agronomic practices that reduce P input requirements and better utilisation of both applied P and existing legacy P reserves in soils (see Chapter 4).

Currently, efforts to combat food insecurity in Sub-Saharan Africa (SSA) focus on agricultural intensification, although an alternative approach emphasising diets, health and the environment has been put forward (Global Panel on Agriculture and Food Systems for Nutrition, 2020). Given the high soil nutrient depletion in this region, replenishing soil fertility is a major component of such efforts (Nziguheba, 2007; Nziguheba et al., 2016). The dominant 'productivist' mentality that still governs the food system, means that farmers and policymakers will continue to favour measures that maintain or enhance production. There remains a reluctance to implement measures that might, for example, take land out of production (Inman et al., 2018) or reduce animal density (Metson et al., 2012; Withers et al., 2020).

Challenge 3.4: Many farmers lack access to phosphorus, threatening their livelihoods

Currently, 1 in 7 farmers cannot access or afford phosphorus fertilisers to increase productivity, reducing their ability to maintain food security and livelihoods. Those farmers most affected are rural smallholder farming families, particularly in less economically developed countries, but also in some more economically developed countries. There are marked global inequalities in access to phosphorus as a resource, leading to substantial inequalities in the distribution of risks to food security.

We currently produce enough food to feed 10 billion people; about 30% more than the global population. As Holt-Giménez et al. (2012) point out, hunger is caused by poverty and inequality, not food scarcity, at a global scale. Those that live on less than US$2 a day, mainly subsistence farming families, cannot afford to buy sufficient food. If the priority is better health for all, global food systems must stop fuelling diets with adverse public health impacts, requiring a systemic change to global food production systems (Global Panel on Agriculture and Food Systems for Nutrition, 2020). A significant proportion of industrially-produced grain crops goes to biofuels and confined animal feedlots rather than food for the 1 billion hungry (Holt-Giménez et al., 2012). Therefore, calls to double food production by 2050 only apply if we continue to prioritise the growing population of livestock and automobiles over hungry people.

Most of the world's food insecure are marginalised families in urban and rural environments. The latter are also typically smallholder farmers (Dixon et al., 2001), who struggle to access fertilisers. According to the FAO (2014), there are more than 500 million family farms globally, producing 80% of the world's food, although Ricciardi et al. (2018) suggest this figure is closer to 35%. In many low-income countries, including in SSA, South Asia, East Asia and the Pacific (excluding China), around 70–80% of farms are smallholder farms (Lowder et al., 2016).

The livelihoods of more than 2 billion people depend on smallholder farms (Lowder et al., 2016). Yet many of these smallholder farmers (particularly in low-income countries) lack sufficient access to P fertiliser markets due to poverty, low purchasing power or because they lack access to credit (Dixon et al., 2001; Druilhe and Barreiro-Hurlé, 2012; IATP, 2005; McIntyre et al., 2009; Runge et al., 2003). Farmers need access to P to replace the P removed in harvested crops and other losses and maintain fertile soils for crop growth. Affordable and sustainable access to P fertilisers is therefore imperative to ensure food security at a national scale, and the food and livelihood security of smallholder and marginal farmers (Weber et al., 2014).

Fertiliser prices are increasing in the long-term and may be subject to further short-term price spikes, (Mew, 2016). In 2008, PR prices spiked by 800%. The cause of this was complex and discussed earlier (see also Chapter 2). Elevated fertiliser prices made farmers more prudent with their fertiliser use and eventually led to a crash in demand for phosphorus. After this price peak, phosphate rock price dropped significantly, but is on average more than two times higher than before the price peak (Mew, 2016) (see Chapter 2).

The use of fertiliser subsidies has been widespread in SSA for decades and is highly controversial. For example, in Nigeria between 1980 and 2010, it has been claimed up to 90% of subsidised fertiliser was bought by officials and sold to private companies (Propcom Mai-karfi, 2014). Only 11% of farmers received subsidised fertilisers, which were often adulterated, damaged, and delayed (Banful et al., 2010; Udo, 2013). Fertiliser subsidies in Africa are politically popular due to their immediacy and visibility (Druilhe and Barreiro-Hurlé, 2012), however, work is needed to ensure they deliver on their aims, and importantly are not impacted by corruption. The African Union during its 30th Assembly of Heads of State and Government in January 2018, declared 2018 as the African Anti-Corruption Year, aiming to ensure better cooperation and mutual legal assistance, and secure stronger international cooperation in dealing with corruption (African Union, 2018).

In some low-income countries, insufficient use of fertilisers and soil erosion has led to substantial nutrient depletion of soils, constraining agricultural productivity. The most vulnerable are subsistence farmers, many of whom are already seeing production levels fall as soil fertility declines, such as African farmers practising shifting cultivation or cultivating marginal lands (Nziguheba et al., 2016), and Brazilian livestock farmers relying on the degrading pastures in the Cerrado region (Pereira et al., 2018). In Africa, fertilisers cost 2 to 6 times more than in Europe, the USA or Asia (Chemonics and IFDC, 2007; Sanchez, 2002), predominantly due to poor infrastructure which can create high costs for over-land transporting, stocking, and distribution (Cordell et al., 2015; Druilhe and Barreiro-Hurlé, 2012). These high costs can undercut the trade competitiveness of agricultural produce (Keyser and Tchale, 2010). African agriculture has enormous potential to drive equitable and sustainable economic growth across the continent, but a keystone in its success will be access to and sustainable management of P, and other nutrients (Chianu et al., 2012). Without change, it has been predicted that insufficient P inputs to African soils could lead to a further 30% reduction in crop yield by 2050 (van der Velde et al., 2014). Of course, the expansion of agriculture in any region of the world should be balanced against the adverse impacts of all agriculture on biodiversity. Greater yields per hectare are desirable in this context, but the conversion of biodiverse habitat to farmland may not be (Benton et al., 2021).

.

3.4 Solutions

Solution 3.1: Managing phosphorus sustainably can support a shift to healthier diets

Global food systems must produce, actively support, and provide access to nutritious food and diets for all. This shift, from 'market-led' to 'sustainable' food security, can reduce phosphorus demand and adverse impacts on ecosystems and society. Concurrently, strategies to deliver better phosphorus sustainability, including circular phosphorus value chains, can benefit agricultural economies, whilst effective monitoring systems, data sharing, and knowledge exchange can ensure strategies adapt to a transforming food system.

Transforming the food system to deliver healthy diets within planetary boundaries implies lower production of red meat and the 'Big Three' grains of wheat, rice and maize (corn), and increasing the diversity of grains (e.g. pulses and lentils) and producing more fruit and vegetables (EAT, 2019). Such a shift may dramatically change fertiliser requirements. Whilst reductions in livestock numbers would significantly reduce global demand for P fertiliser to grow feed (Metson et al., 2012) and increase overall food system P efficiency (Withers et al., 2020), an increase in the production of fruit and vegetables could require more P fertiliser. It could also require more water either from rainfall or through irrigation, which will increase the risk of P loss from farmed soils to waters. Indeed, any change to quantity and types of foods produced will impact mineral P application rates, formulations and timing, the efficiency of P use, and P mobilisation and export within fields, and thus influence P loads entering wastewater treatment works (Forber et al., 2021) and waterbodies (see Chapter 5). Where foods are grown will also affect P demand and the environmental footprint due to different soils, climates, cropping systems and knowledge systems, especially if there is a shift to local and regional food systems. Climate change impacts P input requirements, agricultural output and subsequent losses to water, adding yet another layer of complexity that will vary considerably between different regions (Forber et al., 2018).

Strategies and measures to improve sustainable P use can support the transformation towards more sustainable food systems (Withers et al., 2015). For example, improving PUE can reduce farmers' fertiliser input costs, while reducing their reliance on mineral P fertiliser by increasing access to local recycled P markets, including animal manures and slurries produced on local livestock farms. This, in turn, can create new business opportunities for nutrient recovery in a circular economy, where wastes and residues become products in their own right. Furthermore, providing better information on which farming systems best match P availability in local wastes can support spatial planning and decision-making to optimise agricultural productivity. For example, coupling livestock and arable food production systems to support nutrient reuse between them, and discouraging or providing better options for farming on P fixing soils represent two relevant opportunities to support this transition.

Strategies to deliver sustainable P management must recognise co-benefits and evolve alongside a transforming food system (Table 3.2). The use of 'dynamic adaptive policymaking' (Haasnoot et al., 2013; Walker et al., 2013) supported by effective monitoring systems (e.g. to assess nutrient concentrations in water bodies), data sharing, and effective communication of scientific evidence to both the public and policymakers (Brownlie et al., 2017) can help in this regard.

Table 3.2 Implications for phosphorus (P) of transforming the food system

Sustainable pathways for transforming the food system	Implications and co-benefits for phosphorus
Pathway 1: Produce appropriate food for nutritious diets Systemic changes to the food system are required that address the current disconnect between what we produce (e.g. red meat and the "Big Three" grains: wheat, rice, maize (corn)) versus a recommended balanced diet (Figure 3.4; EAT, 2019). We need to grow more vegetables, fruits, legumes globally.	Producing different foods can change the P fertiliser demand associated with different crop types. For example, shifting from cereal crops to legumes may reduce P fertiliser requirements because the latter is more P-efficient to produce (Lyu et al., 2016). This may also require changes in fertiliser formulations for different crops and geo-climates.
Pathway 2: A shift away from diets with adverse public health impacts Changing diets is one of the single biggest food transformation levers, especially in high meat-consuming countries (Ranganathan et al., 2016). Unhealthy diets (including red meat consumption) are one of the greatest risk factors to human health (e.g. cardiovascular disease, obesity) (GBD 2016 Risk Factors Collaborators, 2017). The triple burden of food insecurity means that 2 billion people are obese or overweight (increasing in every country, including low-income countries); 2 billion people have micronutrient deficiency (e.g. iron, vitamin A); 816 million people are hungry (exacerbated by climate change & conflict, even in high-income countries like Australia where 10-20% are hungry) (FSIN 2018, 2019).	A shift towards healthier plant-based diets globally will result in a lower overall P footprint of the food system, delivering global-scale gains in PUE. For example, the average person in the high-meat consuming nations of Argentina and the USA has a P footprint of over 6 kg P $year^{-1}$, compared with those in India (~1 kg P $year^{-1}$). This is predominantly a result of per capita meat consumption, not total food consumption (Metson et al., 2012). Knock-on effects of dietary change on increased P loading to wastewater treatment centres may provide an additional concentrated source of secondary P for reuse if recovered effectively (Forber et al., 2021), or greater adverse impacts on aquatic ecosystems, if not recovered before the discharge of effluent to waters.

Sustainable pathways for transforming the food system	Implications and co-benefits for phosphorus
Pathway 3: Decreased environmental footprints of food production and consumption The cost of the environmental and health burden of the current food system far exceeds the value of global agriculture (Collins et al., 2016; Zhang et al., 2017). Climate change, water scarcity and pollution, energy scarcity and pollution, obesity and the non-communicable food-related disease epidemic (diabetes and cardiovascular health, cancers) means business as usual commodity-crop based agriculture is not an option.	Measures to reduce the environmental footprints of food production often have a lower P footprint (Metson et al., 2014). For example, millet is not only a nutritionally dense grain (high in calcium and iron) but has a low carbon footprint and low pesticide and fertiliser requirement (ICRISAT, 2018). Reducing P losses from agriculture can reduce water pollution by minimising fertiliser losses in eroded topsoil, surface entrainment of P-rich manures and slurries, and the flushing of desorbed P through P-saturated soils and groundwaters to rivers, lakes, estuaries and the coastal zone.
Pathway 4: Reduce food waste in the supply chain Pre- and post-harvest food waste globally are estimated at 30-50% (varying widely across value chains and regions). This results in waste of embodied energy and resources (e.g. nutrients) used to produce, process and transport the food, and occupation of valuable space in landfills from which methane is released upon decomposition, in addition to the cost to consumers and food producers (FAO, 2011).	Reducing food waste directly reduces P wastage because, like all organic waste, food processing waste and food waste contains P and has a P footprint associated with its production. Currently, 80% of input P is wasted along the whole P value chain (Cordell et al., 2009), half of which could be post-harvest. Reducing this loss would reduce global demand for mined non-renewable phosphate and/or make P more available for reuse such as the use of compost or digestate.

Sustainable pathways for transforming the food system	Implications and co-benefits for phosphorus
Pathway 5: Shorten food value chains (where appropriate) Producing food closer to where it is consumed can increase food security in the face of shocks like fuel shortages or floods that affect transport routes. Shorter supply chains reduce energy, waste, middle-management, transport and cooling, to deliver the same unit of food.	This pathway presents a potential trade-off for phosphorus. There is a risk that local food systems can be potentially less P efficient at the farm scale, depending on local soils, technical and knowledge systems. However, at the larger system scale, this would reduce P wastage in the post-harvest value chain by, for example, reducing the P embodied in food commodities that end up as food waste due to spoilage or market excess.
Pathway 6: Increase food access Currently, over 800 million people lack sufficient access to food. There is a need to increase financial access, physical access, and food literacy, to in turn improve the health, productivity, quality of life and livelihoods of this food insecure group.	Most of the world's food insecure are rural smallholder farming families – the same group who struggle to access fertilisers. Around 1 in every 7 farmers cannot access fertiliser markets (McIntyre et al., 2009). Fertiliser prices are increasing and may be subject to further price spikes. Increasing access to fertilisers or local nutrients (or access to loans/credit) can increase crop yields and hence income and food security for farming families.
Pathway 7: Consider the food system's whole value chain, beyond agriculture The FAO and the Organisation for Economic Co-operation and Development (OECD) have adopted the term 'food systems' to acknowledge and assess the complex links between consumption patterns, food processing and retail value chains, farmer livelihoods, public health, environment and agricultural inputs. Adoption of this consistent framework will provide insights into opportunities for addressing unsustainable practices across currently obscured value chains.	In addition to on-farm P management, such as the timing of fertiliser applications to crops and grass and the management of manures and slurries, many opportunities occur before or after the farm, like recycling P in organic waste (or reducing losses), fertiliser production, food storage, processing, and retail. In addition, shifting consumer preferences can have a significant impact up the value chain, in terms of how sustainably crops are grown (including their P efficiency), and which foods are produced (such as animal or plant-based proteins).

Solution 3.2: Shift global consumption of animal products towards plant-based diets

Reduced consumption of animal products especially from intensive production systems in some regions may reduce global agricultural phosphorus demand and contribute to healthier environments. Increased awareness amongst policymakers and the public of the environmental impacts of phosphorus use in food production, and the human health risks of excessive consumption of animal products, will be an essential driver of change. Knowledge exchange between academics, stakeholders and the public can help identify solutions to support a transition to more phosphorus sustainable consumer behaviour, as could policy and regulatory changes (including internalising the environmental costs into food pricing).

Reduced consumption of animal products from concentrated feeding operations in some regions will significantly reduce global agricultural P demand (Elser, 2012; Ma et al., 2012; Metson et al., 2012; Schröder et al., 2011; Suh and Yee, 2011). Reducing the consumption of animal products (for those people eating excess amounts) will contribute to healthier humans and environments (EAT, 2019; Elser and Bennett, 2011), especially for high-meat consuming countries. Plant-based diets typically have a lower P footprint; 1 kg of P fertiliser can produce over 3000 kg of starchy roots or 16 kg of beef (Metson et al., 2012). Hence, if diets shift to plant-based, this could reduce global P demand by some 50%. Whilst this may not be realistic in the short term (e.g. 5 years), even modest shifts to plant-based diets will have a significant impact on P demand (Metson et al., 2012). However, such a shift can increase P loadings to wastewater treatment works instead of agriculture, although if effectively recovered this could provide an additional source of secondary P for reuse in agricultural systems (Fober et al., 2021). If this P is not recovered, however, P availability and loading impacts on aquatic ecosystems could increase. Therefore, a shift to more plant-based diets will require more investment in P recovery technologies and wastewater treatment infrastructure in parallel, if off-site P impacts are to be managed.

Changing eating behaviours is possible (IPCC, 2019; Loken and DeClerck, 2020; Ranganathan et al., 2016). Improving public and policy awareness of the impacts of P use in food production will help to change societal and policy support for sustainable P practices. Currently, it would be reasonable to presume most people do not buy foods based on the P impacts of their production. A combination of factors influences each consumer's buying choices, such as cost, convenience, availability, taste, appearance, positioning (e.g. at eye level), marketing health, environmental impacts (e.g. impacts on climate change, biodiversity), animal welfare, and buying habits. It is, therefore, important to ensure that products with low P footprints are aligned with these criteria, so consumers are more likely to purchase them (see Chapter 8). Knowledge exchange between social scientists, stakeholders and the public will help identify solutions to support a transition to more P sustainable consumer behaviour. Efforts are increasing in this area. For example, networks and platforms have been developed at the national and international scales to support knowledge exchange (e.g. the European Sustainable Phosphorus Platform, the Sustainable Phosphorus Alliance, and the Global Phosphorus Research Initiative). These bodies support networks across multiple sectors providing evidence on sustainable P issues across different scales. The combined efforts of these groups are powerful, and they offer an essential conduit through which emerging approaches and evidence can be effectively integrated across scales to support the transition of food systems towards greater P security. For example, recent developments across multiple fields in P sustainability include bringing together international experts to identify national-scale improvements (Macintosh et al., 2019), conducting stakeholder analyses to support coordination across sectors (Lyon et al., 2020), identifying barriers and solutions to fostering pro-environmental behaviour (Okumah et al., 2020), and delivering cost-benefit analyses including impacts on human health associated with an increase in P recycling (Tonini et al., 2019).

Solution 3.3: Integrated landscape strategies to improve phosphorus use efficiency and reduce losses

There is an opportunity to develop novel land-use planning approaches to support more sustainable phosphorus use across multiple and interacting contexts. These include agricultural production, ecosystem and human health, local economies and regional capacity for institutional planning and coordination. Sustainable farming systems in which animal and crop production are more integrated and animal residues and manures are treated as valuable phosphorus resources, will support efforts to increase phosphorus use efficiency within landscapes while reducing negative impacts on aquatic and terrestrial ecosystems.

There is a recognised need for integrated land-use planning that considers how to balance multiple needs including resource stocks and flows, energy dynamics, flood retention, urban regeneration, biodiversity, and climate change mitigation (Estrada-Carmona et al., 2014; Macintosh et al., 2019). Robust data on soil P content and the amount of P applied to soils in fertilisers and manures and other residual flows will support more effective P management in sustainable agricultural intensification (Macintosh et al., 2019). Methods to mine 'legacy P' (i.e. P stored in soil that is not immediately available for plant uptake), such as through P efficient cultivars, root management, rhizosphere microbiome engineering and rhizosphere interactions (Lemaire et al., 2021; Rowe et al., 2016; Schneider et al., 2019), can be used in combination with careful management to improve PUE throughout the food production chain, from mine to fork (see Chapter 4).

Field data suggest that sustainable agricultural intensification can protect biodiversity by boosting yields on existing farmland and sparing undisturbed habitats from being brought into production (Balmford et al., 2018; Garnett et al., 2013). Whilst high yield farming generates more externalities per unit area (e.g. greenhouse gas emissions and nutrient losses), Balmford et al. (2018) argue these metrics underestimate the impacts of low yield farming. In some areas, increases in yield will be compatible with environmental improvements. In others, yield reductions or land reallocation will be necessary to ensure sustainability and to deliver other desirable benefits (e.g. wildlife conservation, carbon storage, flood protection, and recreation). For example, the opportunity exists to better integrate nature-based solutions within agricultural catchments to deliver both reduced greenhouse gas emissions and more sustainable P use through the food system (Seddon et al., 2019). It is important to recognise that urbanisation and food system efficiency drive important feedbacks with climate systems. An overall increase in food production does not mean yields must increase everywhere or at any cost. The challenge is context- and location-specific and requires careful land-use planning and reform (Balmford et al., 2018) based on sound scientific evidence to support decision-making (Garnett et al., 2013).

Solution 3.4: Better support for smallholder farmers

Affordable access to sustainable phosphorus sources is imperative to ensure food provision for all and to protect the livelihoods of smallholder and marginal farmers. Multiple options exist to help improve phosphorus access in these communities. These include access to credit, extension services, investment in sustainable infrastructure (such as local phosphorus recycling systems from food waste and sanitation where available), and knowledge exchange to support better phosphorus use efficiency and recycling. Developing the capacity to recycle phosphorus from local and regional food systems where available can help to shift reliance away from mineral phosphorus fertilisers.

Smallholder farmers are particularly at risk from volatility in future P prices. Therefore, P stakeholders need to plan for uncertainty and develop adaptation strategies that consider P demand management, including measures targeting increased efficiency in the value chain and selecting for low P footprint nutritious foods. Improving farmer and food stakeholders' adaptive capacity, such as technical know-how, access to equipment and financial resources, provision of extension services and training for smallholder communities and regions to recycle P in local waste streams (see Chapters 6 and 7), may help to diversify P sources and alleviate reliance on expensive mineral P fertiliser. In some cases, vulnerable farmers can adapt to both P and climate exposure through diversification strategies, such as growing more P-efficient and climate-resilient crops or supplementing income with off-farm employment such as agri-tourism (Cordell et al., 2017). Policymakers need to support and enable such measures, to ensure that socio-economic costs of transitioning towards more sustainable practices do not punish the most vulnerable in society.

A substantial barrier obstructing fertiliser use in SSA is farmer poverty, promulgated by the poverty trap in smallholder agriculture (Hanjra et al., 2009). To combat this, government schemes to subsidise fertilisers have been widespread across SSA (AGRF, 2018). At the 2006 Africa Fertiliser Summit, the African Union signed the 'Abuja Declaration on Fertiliser for an African Green Revolution' calling for the elimination of all taxes and tariffs on fertiliser and increased fertiliser use (African Development Bank, 2021). As of 2017, 47 of the African Union states had not achieved this, due to a lack of harmonisation on policy and regulation frameworks, lack of tax incentives, trade barriers, and poor quality control on fertilisers (AGRF, 2018). Ironically, fertiliser subsidies have played a role in this and remain controversial, with evidence of success (Seck et al., 2010), failure (Druilhe and Barreiro-Hurlé, 2012; Jayne and Rashid, 2013), and political misuse (e.g. politically motivated regional allocation of subsidies to win votes) (Banful et al., 2010). However, whilst it is clear that P inputs to nutrient-deficient soils in Africa are urgently needed, this should be delivered in coordination with education and training for farmers to optimise sustainable nutrient practices, especially in terms of appropriate mineral P fertiliser application.

Increasing soil fertility through the addition of nutrients is essential to address soil P deficiency in SSA (Vanlauwe and Giller, 2006). However, mineral fertilisers are not the only means available, and opportunities exist to develop the capacity to fertilise soils using other P sources. Renewable P fertilisers can theoretically be processed from any locally available raw organic material that has a high enough P concentration, contains minimal contaminants, meets local soil and farmer's agronomic needs and can be converted into bioavailable form through cost-effective means (Cordell et al., 2011). Raw sources could include food waste, manure, algae, bones, crop waste and human excreta. Using such sources can also provide co-benefits to environmental and human health in addition to food security. Currently, 54% of the population in SSA does not have access to safe sanitation (WHO/UNICEF JMP, 2017). Aspirational goals to improve sanitation (e.g. the United Nations SDG 6) provide an opportunity to lead global sanitation innovation by building P reuse into sanitation as standard (urine-diverting toilets being one example) (Udert et al., 2016) (see Chapter 7).

Direct application of local phosphate rock with organic materials has also shown to be a successful cheaper alternative to superphosphates on acidic soils (Chianu et al., 2012; Sanchez, 2002). Opportunities that make use of local indigenous knowledge have proven successful, such as Zai pits (small planting pits, usually filled with organic matter to create microenvironments) that reduce soil erosion, retain nutrients (Danjuma and Mohammed, 2015) and optimise plant nutrient uptake from P-rich organic materials. Investment in sustainable infrastructure (such as local P recycling systems from food waste and sanitation) and knowledge exchange to support better P use efficiency and recycling is required. In some cases, extension services and training will be needed to raise awareness of local options for farmers (AGRF, 2018). In other regions, particularly low-income countries and vulnerable communities, increasing affordable access to sustainable P sources will be a priority. Opportunities for achieving this range from access to credit and investment in sustainable infrastructure (such as local P recycling systems from food waste and sanitation where available) to extension services and knowledge exchange to support better P use efficiency and recycling.

References

African Union. 2018. Winning the Fight against Corruption: A Sustainable Path to Africa's Transformation. https://au.int/sites/default/files/pressreleases/33575-pr-note_to_editors_on_the_theme_of_the_30th_au_summit.pdf (accessed 5 August 2021).

African Development Bank. 2021. Africa Fertilizer Financing Mechanism. https://www.afdb.org/en/affm (accessed 8 September 2021).

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Work. Pap. No. 12-03. Rome, FAO.

Bahadur ID, K.K., G.M. Dias, A. Veeramani, C.J. Swanton, D. Fraser, et al. 2018. When too much isn't enough: Does current food production meet global nutritional needs? PLoS ONE 13(10): e0205683. doi: 10.1371/journal.pone.0205683.

Bajželj, B., K.S. Richards, J.M. Allwood, P. Smith, J.S. Dennis, et al. 2014. Importance of food-demand management for climate mitigation. Nat. Clim. Chang. 4(10): 924–929. doi: 10.1038/nclimate2353.

Balmford, A., T. Amano, H. Bartlett, D. Chadwick, A. Collins, et al. 2018. The environmental costs and benefits of high-yield farming. Nat. Sustain. 1(9): 477–485. doi: 10.1038/s41893-018-0138-5.

Banful, A.B., E. Nkonya, and V. Oboh. 2010. Constraints to Fertilizer Use in Nigeria: Insights from Agricultural Extension Service. IFPRI Discussion paper 01010. Washington, D.C, International Food Policy Research Institute. https://ebrary.ifpri.org/digital/collection/p15738coll2/id/3420 (accessed 24 September 2021).

Batjes, N.H. 2011. Global distribution of soil phosphorus retention potential. ISRIC Report 2011/06. ISRIC – World Soil Information, Wageningen, Netherlands. https://edepot.wur.nl/185289 (accessed 5 August 2021).

Baulcombe, D., I. Crute, B. Davies, J. Dunwell, M. Gale, et al. 2009. Reaping the benefits: science and the sustainable intensification of global agriculture. RS Policy document 11/09. Royal Society, London, UK. https://royalsociety.org/-/media/Royal_Society_Content/policy/publications/2009/4294967719.pdf (accessed 5 August 2021).

Benton, T.G., C. Bieg, H. Harwatt, R. Pudasaini, L. Wellesley. 2021. Food system impacts on biodiversity loss. Three levers for food system transformation in support of nature. Research Paper, Energy, Environment and Resources Programme. Chatham House, London, UK.

Benton, T.G. 2019. Using scenario analyses to address the future of food. EFSA J. 17(S1): e170703. doi: 10.2903/J.EFSA.2019.E170703.

Benton, T.G. 2016. Sustainable Intensification. In: Pritchard, B., Oritz, R., and Shekar, M., editors, Routledge Handbook of Food and Nutrition Security. Routledge, Abingdon. pp.95–109.

Beusen, A.H.W., A.F. Bouwman, L.P.H. Van Beek, J.M. Mogollón, and J.J. Middelburg. 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences 13(8): 2441–2451. doi: 10.5194/bg-13-2441-2016.

Bock, A.-K., P. Maragkoudakis, J. Wollgast, S. Caldeira, A. Czimbalmos, et al. 2014. Tomorrow`s healthy society - Research priorities for foods and diets. Final Report. JRC Foresight Study, EUR 26821. Publications Office of the European Union, Luxembourg. doi: 10.2788/14108.

Brownlie, W.J., H.J. Woods, K.E. Waters, A.L. Moore, A.M Bruce, et al. 2017. Freshwater science for the benefit of society: a perspective from early career researchers. Inl. Waters 7(2): 227–235. doi: 10.1080/20442041.2017.1326793.

Burlingame, B., Dernin, S., Nutrition and Consumer Protection Division FAO. 2012. Sustainable Diets and Biodiviersity: Directions and Solutions for Policy, Research and Action. Proceedings of the International Scientific Symposium, Biodiversity and sustainable Diets United against Hunger, 3-5 November 2010. FAO, Rome.

Carpenter, S.R., P.L. Pingali, E.M. Bennett, and M.B. Zurek, editors. 2005. Ecosystems and Human Well-being: Scenarios, Volume 2. Findings of the Scenarios Working Group, The Millennium Ecosystem Assessment. Island Press, Washington DC.

Challinor, A.J., W.N. Adger, T.G. Benton, D. Conway, M. Joshi, et al. 2018. Transmission of climate risks across sectors and borders. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 376(2121): 20170301. doi: 10.1098/rsta.2017.0301.

Chemonics and IFDC. 2007. Fertilizer Supply and Costs in Africa. Chemonics International Inc. and the International Center for Soil Fertility and Agricultural Development, Muscle Shoals, AL, USA. https://www.inter-reseaux.org/wp-content/uploads/IFDC__Chemonics-FertilizerSupplyandCostsinAfrica_Study_for_BMGF-2.pdf (accessed 24 September 2021).

Chianu, J.N., J.N. Chianu, and F. Mairura. 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron. Sustain. Dev. 32(2): 545–566. doi: 10.1007/s13593-011-0050-0.

Childers, D.L., J. Corman, M. Edwards, and J.J. Elser. 2011. Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle. Bioscience 61(2): 117–124. doi: 10.1525/bio.2011.61.2.6.

Collins, A.L., J.P. Newell Price, Y. Zhang, R. Gooday, P.S. Naden, et al. 2018. Assessing the potential impacts of a revised set of on-farm nutrient and sediment 'basic' control measures for reducing agricultural diffuse pollution across England. Sci. Total Environ. 621: 1499–1511. doi: 10.1016/j.scitotenv.2017.10.078.

Collins, A.L., Y.S. Zhang, M. Winter, A. Inman, J.I. Jones, et al. 2016. Tackling agricultural diffuse pollution: What might uptake of farmer-preferred measures deliver for emissions to water and air? Sci. Total Environ. 547: 269–281. doi: 10.1016/j.scitotenv.2015.12.130.

Cordell, D. 2010. The Story of Phosphorus: S ustainability implications of global phosphorus scarcity for food security. Ph.D. Thesis, Linköping Univ. Linköping, Sweden. http://liu.diva-portal.org/smash/get/diva2:291760/FULLTEXT01.pdf (accessed 18 October 2021).

Cordell, D., E. Dominish, M. Esham, B. Jacobs. 2017. Towards Phosphorus and Climate Smart Agriculture in Sri Lanka. Report prepared by the Institute for Sustainable Futures at University of Technology Sydney in collaboration with Sabaragamuwa University of Sri Lanka, Sydney, Australia. http://hdl.handle.net/10453/118045 (accessed 5 August 2021).

Cordell, D., J.O. Drangert, and S. White. 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Chang. 19(2): 292–305. doi: 10.1016/j.gloenvcha.2008.10.009.

Cordell, D., A. Rosemarin, J.J. Schröder, A.L. Smit. 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere 84, 747–758. https://doi.org/10.1016/j.chemosphere.2011.02.032.

Cordell, D., A. Turner, and J. Chong. 2015. The hidden cost of phosphate fertilizers: mapping multi-stakeholder supply chain risks and impacts from mine to fork. Glob. Chang. Peace Secur. 27(3): 323–343. doi: 10.1080/14781158.2015.1083540.

Courtney, H., J. Kirkland, and P. Viguerie. 1997. Strategy under uncertainty. Harv. Bus. Rev. 75: 67–79.

Danjuma, M., and S. Mohammed. 2015. Zai Pits System: A Catalyst for Restoration in the Drylands. IOSR Journal of Agriculture and Veterinary Science 8(2), 1–4. doi: 10.9790/2380-08210104.

Darmon, N., and A. Drewnowski. 2015. Contribution of food prices and diet cost to socioeconomic disparities in diet quality and health: a systematic review and analysis. Nutr. Rev. 73(10): 643–660. doi: 10.1093/nutrit/nuv027.

de Ridder, M., S. de Jong, J. Polchar, S. Lingemann. 2012. Risks and Opportunities in the Global Phosphate Rock Market. Robust Strategies in Times of Uncertainty. Report No 17 | 12 | 12, The Hague Centre for Strategic Studies, The Hague, Netherlands.

de Vries, M., C.E. van Middelaar, I.J.M. de Boer. 2015. Comparing environmental impacts of beef production systems: A review of life cycle assessments. Livest. Sci. 178, 279–288. https://doi.org/10.1016/j.livsci.2015.06.020.

Development Initiatives. 2018. 2018 Global Nutrition Report: Shining a light to spur action on nutrition. Development Initiatives, Bristol, UK. https://globalnutritionreport.org/d7447a (accessed 24 September 2021).

Dixon, J.A., M. Hall, A. Gulliver, D.P. Gibbon (2001). Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World. Rome, FAO and World Bank.

Doody, D.G., P.J. Withers, R.M. Dils, R.W. McDowell, V. Smith, et al. 2016. Optimizing land use for the delivery of catchment ecosystem services. Front. Ecol. Environ. 14(6): 325–332. doi: 10.1002/fee.1296.

Druilhe, Z., and J. Barreiro-Hurlé. 2012. Fertilizer subsidies in sub-Saharan Africa. ESA Working Papers 288997, Agricultural Development Economics Division (ESA), Food and Agriculture Organization of the United Nations.. doi: 10.22004/ag.econ.288997.

Durst, P.B., D. V Johnson, R.N. Leslie, and K. Shono, editors. 2010. Forest insects as food: humans bite back. Proceedings of a workshop on Asia-Pacific resources and their potential for development, 19-21 February 2008, Chiang Mai, Thailand. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand.

EAT. 2019. Food Planet Health: Healthy Diets From Sustainable Food Systems. Summary Report of the EAT-Lancet Commission. EAT, Oslo, Norway.

Elser, J.J. 2012. Phosphorus: a limiting nutrient for humanity? Curr. Opin. Biotechnol. 23: 833–838. doi: 10.1016/j.copbio.2012.03.001.

Elser, J.J, and E. Bennett. 2011. Phosphorus cycle: A broken biogeochemical cycle. Nature 478(7367): 29–31. doi: 10.1038/478029a.

Estrada-Carmona, N., A.K. Hart, F.A.J. DeClerck, C.A. Harvey, and J.C. Milder. 2014. Integrated landscape management for agriculture, rural livelihoods, and ecosystem conservation: An assessment of experience from Latin America and the Caribbean. Landsc. Urban Plan. 129: 1–11. doi: 10.1016/J.LANDURBPLAN.2014.05.001.

European Commission. 2013. Scoping Study – Delivering on EU food safety and nutrition in 2050 -Scenarios of future change and policy responses. European Commission Directorate General for Health and Consumers. https://ec.europa.eu/food/system/files_en?file=2016-10/final_report_scoping_study_en.pdf (accessed 4 August 2021.

Falkowski, P., R.J. Scholes, E. Boyle, J. Canadell, D. Canfield, et al. 2000. The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. Science. 290: 291–296. doi: 10.1126/science.290.5490.291.

FAO, IFAD, UNICEF, WFP, and WHO. 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. FAO, Rome.

FAO. 2017. FAOSTAT. Food Agric. Data. http://www.fao.org/faostat/en/#data.

FAO. 2014. The State of Food and Agriculture Innovation 2014. Innovation in Family Farming. FAO, Rome.

FAO. 2009. Declaration of the World Summit on Food Security, WSFS 2009/2. FAO, Rome, http://www.fao.org/3/k6050e/k6050e.pdf (accessed 5 August 2021).

FAO, IFAD, UNICEF, WFP, and WHO. 2018. The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutritionFAO, Rome.

Fears, R., C. Canales, V. ter Meulen, and J. von Braun. 2019. Transforming food systems to deliver healthy, sustainable diets—the view from the world's science academies. Lancet Planet. Heal. 3(4): e163–e165. doi: 10.1016/S2542-5196(19)30038-5.

Fischer, P., R. Pöthig, B. Gücker, and M. Venohr. 2018. Phosphorus saturation and superficial fertilizer application as key parameters to assess the risk of diffuse phosphorus losses from agricultural soils in Brazil. Sci. Total Environ. 630: 1515–1527. doi: 10.1016/j.scitotenv.2018.02.070.

Fischer, P., R. Pöthig, and M. Venohr. 2017. The degree of phosphorus saturation of agricultural soils in Germany: Current and future risk of diffuse P loss and implications for soil P management in Europe. Sci. Total Environ. 599–600: 1130–1139. doi: 10.1016/j.scitotenv.2017.03.143.

Fitzpatrick, I., R. Young, and R. Barbour. 2017. The Hidden Cost of UK Food. Revised Edition 2019. Sustainable Food Trust, Bristol, UK.

Forber, K.J., P.J.A. Withers, M.C. Ockenden, P.M. Haygarth. 2018. The Phosphorus Transfer Continuum: A Framework for Exploring Effects of Climate Change. Agric. Environ. Lett. 3, 180036. https://doi.org/10.2134/AEL2018.06.0036.

FSIN. 2018. Global Report on Food Crises 2018. Food Security Information Network (FSIN), UN World Food Programme, Rome. https://www.wfp.org/publications/global-report-food-crises-2018 (accessed 5 August 2021).

FSIN. 2019. Global Report on Food Crises 2019. Food Security Information Network (FSIN), UN World Food Programme, Rome. https://www.wfp.org/publications/2019-global-report-food-crises (accessed 5 August 2021).

Garnett, T., M.C. Appleby, A. Balmford, I.J. Bateman, T.G. Benton, et al. 2013. Sustainable Intensification in Agriculture: Premises and Policies. Science. 341(6141): 33–34. doi: 10.1126/science.1234485.

GBD 2016 Risk Factors Collaborators. 2017. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet 390, 1345–1422.doi: 10.1016/S0140-6736(17)32366-8.

GBD 2017 Risk Factors Collaborators. 2018. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 392(10159): 1923–1994. doi: 10.1016/S0140-6736(18)32225-6.

Global Panel on Agriculture and Food Systems for Nutrition. 2020. Future Food Systems: For people, our planet, and prosperity. London, UK.

Haasnoot, M., J.H. Kwakkel, W.E. Walker, and J. ter Maat. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang. 23(2): 485–498. doi: 10.1016/J.GLOENVCHA.2012.12.006.

Hanjra, M.A., T. Ferede, and D.G. Gutta. 2009. Reducing poverty in sub-Saharan Africa through investments in water and other priorities. Agric. Water Manag. 96(7): 1062–1070. doi: 10.1016/J.AGWAT.2009.03.001.

SustainAbility and WWF. 2018. Sustainable Food Systems and Diets: A review of multi-stakeholder initiatives. SustainAbility and WWF-UK. https://www.wwf.org.uk/sites/default/files/2018-10/59078%20Sustainable%20food%20systems%20report%20-%20ONLINE.pdf (accessed 5 August 2021).

High Level Forum. 2019. High Level Forum on Sustainable Plant Nutrition: Towards a new paradigm for sustainable plant nutrition, 18-20 November 2019, Versailles, France. International Fertilizer Association, Paris, France. https://www.highlevelforum.org/ (accessed 24 September 2021).

Hoekstra, A.Y. 2012. The hidden water resource use behind meat and dairy. Anim. Front. 2(2): 3–8. doi: 10.2527/af.2012-0038.

Holt-Giménez, E., A. Shattuck, M. Altieri, H. Herren, and S. Gliessman. 2012. We Already Grow Enough Food for 10 Billion People … and Still Can't End Hunger. J. Sustain. Agric. 36(6): 595–598. doi: 10.1080/10440046.2012.695331.

Hunter, M.C.M., R.G.R. Smith, M.E. Schipanski, L.L.W. Atwood, D.A. Mortensen, et al. 2017. Agriculture in 2050: Recalibrating Targets for Sustainable Intensification. Bioscience 67(4): 386–391. doi: 10.1093/biosci/bix010.

IATP. 2005. Ten ways to fix agricultural trade: Benchmarks for the Hong Kong Ministerial, excerpted from "Sailing Close To The Wind: Navigating The Hong Kong WTO Ministerial". Institute for Agriculture & Trade Policy, Minneapolis, USA. https://www.iatp.org/sites/default/files/451_2_37141.pdf (accessed 24 September 2021).

ICRISAT. 2018. UN International Year of Millets. International Crops Research Insttitute for the Semi-Arid Tropics (ICRISAT). http://www.icrisat.org/wp-content/uploads/2017/10/UN-International-Year-of-Millets-V3-20-Oct.pdf (accessed 8 July 2021).

IFA. 2011. Feeding the Earth brief: Food Prices and Fertilzser Markets, Factors influencing variations in fertilizer market conditions. International Fertilizer Association, Paris, France. https://www.fertilizer.org/images/Library_Downloads/2011_ifa_food_prices.pdf.

Inman, A., M. Winter, R. Wheeler, E. Vrain, A. Lovett, et al. 2018. An exploration of individual, social and material factors influencing water pollution mitigation behaviours within the farming community. Land Use policy 70: 16–26. doi: 10.1016/j.landusepol.2017.09.042.

IPCC. 2018. Summary for Policymakers. In: Global Wwarming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways (in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, et al., editors). https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf (accessed 22 July 2021).

IPCC. 2019. Climate Change and Land,: an IPCC Sspecial Rreport on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Shukla, P.R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, et al., editors.Prep. under Sci. Leadersh. all three IPCC Work. Groups Coop. with Task Force Natl. Greenh. Gas Invent. Support. by Work. Gr. III Tech. Support Unit https://www.ipcc.ch/srccl/ (accessed 22 July 2021).

Jacks, D. 2018. From Boom to Bust: A Typology of Real Commodity Prices in the Long Run. NBER Working Paper 18874, National Bureau of Economic Research. doi: 10.3386/w18874.

Jayne, T.S., and S. Rashid. 2013. Input subsidy programs in sub-Saharan Africa: a synthesis of recent evidence. Agric. Econ. 44(6): 547–562. doi: 10.1111/agec.12073.

Johnes, P.J. 2007. Uncertainties in annual riverine phosphorus load estimation: Impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. J. Hydrol. 332(1–2): 241–258. doi: 10.1016/j.jhydrol.2006.07.006.

Kahiluoto, H., M. Kuisma, A. Kuokkanen, M. Mikkilä, and L. Linnanen. 2014. Taking planetary nutrient boundaries seriously: Can we feed the people? Glob. Food Sec. 3(1): 16–21. doi: 10.1016/j.gfs.2013.11.002.

Keyser, J., and H.Tchale. Quantitative Value Chain Analysis: An Application to Malawi. World Bank Policy Research Working Papers No. 5242. World Bank, Washington D.C.doi: 10.1596/1813-9450-5242.

Khabarov, N., and M. Obersteiner. 2017. Global Phosphorus Fertilizer Market and National Policies: A Case Study Revisiting the 2008 Price Peak. Front. Nutr. 4: 22. doi: 10.3389/fnut.2017.00022.

Kummu, M., H. De Moel, M. Porkka, S. Siebert, O. Varis, et al. 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci. Total Environ. 438: 477–489. doi: 10.1016/j.scitotenv.2012.08.092.

Lambin, E.F., H.K. Gibbs, L. Ferreira, R. Grau, P. Mayaux, et al. 2013. Estimating the world's potentially available cropland using a bottom-up approach. Glob. Environ. Chang. 23(5): 892–901. doi: 10.1016/J.GLOENVCHA.2013.05.005.

Leiber, F., T. Gelencsér, A. Stamer, Z. Amsler, J. Wohlfahrt, et al. 2015. Insect and legume-based protein sources to replace soybean cake in an organic broiler diet: Effects on growth performance and physical meat quality. Renewable Agriculture and Food Systems 32(1): 21–27. doi: 10.1017/S1742170515000496.

Leip, A., G. Billen, J. Garnier, B. Grizzetti, L. Lassaletta, et al. 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environ. Res. Lett. 10(11): 115004. doi: 10.1088/1748-9326/10/11/115004.

Lemaire, G., L. Tang, G. Bélanger, Y. Zhu, M.H. Jeuffroy. 2021. Forward new paradigms for crop mineral nutrition and fertilization towards sustainable agriculture. Eur. J. Agron. 125, 126248. https://doi.org/10.1016/J.EJA.2021.126248.

Loken, B., and F. DeClerck. 2020. Diets for a Better Future: Rebooting and Reimagining Healthy and Sustainable Food Systems in the G20. EAT, Oslo, Norway.

Lou, H., S. Yang, C. Zhao, Q. Zhou, J. Bai, et al. 2015. Phosphorus risk in an intensive agricultural area in a mid-high latitude region of China. Catena 127: 46–55. doi: 10.1016/j.catena.2014.12.013.

Lowder, S.K., J. Skoet, and T. Raney. 2016. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. World Dev. 87: 16–29. doi: 10.1016/j.worlddev.2015.10.041.

Lyon, C., D. Cordell, B. Jacobs, J. Martin-Ortega, R. Marshall, et al. 2020. Five pillars for stakeholder analyses in sustainability transformations: The global case of phosphorus. Environ. Sci. Policy 107: 80–89. doi: 10.1016/j.envsci.2020.02.019.

Lyu, Y., H. Tang, H. Li, F. Zhang, Z. Rengel, et al. 2016. Major Crop Species Show Differential Balance between Root Morphological and Physiological Responses to Variable Phosphorus Supply. Front. Plant Sci. 7: 1939. doi: 10.3389/fpls.2016.01939.

Ma, L., G.L.L. Velthof, F.H.H. Wang, W. Qin, W.F.F. Zhang, et al. 2012. Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. Sci. Total Environ. 434: 51–61. doi: 10.1016/j.scitotenv.2012.03.028.

Machovina, B., K.J. Feeley, and W.J. Ripple. 2015. Biodiversity conservation: The key is reducing meat consumption. Sci. Total Environ. 536: 419–431. doi: 10.1016/j.scitotenv.2015.07.022.

Macintosh, K.A., D.G. Doody, P.J.A. Withers, R.W. McDowell, D.R. Smith, et al. 2019. Transforming soil phosphorus fertility management strategies to support the delivery of multiple ecosystem services from agricultural systems. Sci. Total Environ. 649: 90–98. doi: 10.1016/j.scitotenv.2018.08.272.

Maggio, A., T. Van Criekinge, and J. Malingreau. 2015. Global Food Security 2030 – Assessing Trends in View of Guiding Future EU Policies. JRC Science and Policy Report 94867. Publications Office of the European Union, Luxembourg doi: 10.2788/5992.

Martin, D. 2014. Edible: An Adventure Into the World of Eating Insects and the Last Great. New Harvest, Houghton Mifflin Harcourt, New York.

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural Intensification and Ecosystem Properties. Science. 277(5325): 504–509. doi: 10.1126/science.277.5325.504.

McAuliffe, G.A., T. Takahashi, and M.R.F. Lee. 2018a. Framework for life cycle assessment of livestock production systems to account for the nutritional quality of final products. Food Energy Secur. 7(3): e00143. doi: 10.1002/fes3.143.

McAuliffe, G.A., T. Takahashi, R.J. Orr, P. Harris, and M.R.F. Lee. 2018b. Distributions of emissions intensity for individual beef cattle reared on pasture-based production systems. J. Clean. Prod. 171: 1672–1680. doi: 10.1016/j.jclepro.2017.10.113.

McIntyre, B.D., H.R. Herren, J. Wakhungu, R.T. Watson, editors. 2009. Agriculture at a Crossroads. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) Global Report. Island Press, Washington, D.C. https://wedocs.unep.org/handle/20.500.11822/8590.

Metson, G.S., V.H. Smith, D.J. Cordell, D.A. Vaccari, J.J. Elser, et al. 2014. Phosphorus is a key component of the resource demands for meat, eggs, and dairy production in the United States. Proc. Natl. Acad. Sci. 111(46): E4906–E4907. doi: 10.1073/pnas.1417759111.

Metson, G.S., E.M. Bennett, and J.J. Elser. 2012. The role of diet in phosphorus demand. Environ. Res. Lett. 7(4): 044043. doi: 10.1088/1748-9326/7/4/044043.

Mew, M.C. 2016. Phosphate rock costs, prices and resources interaction. Sci. Total Environ. 542: 1008–1012. doi: 10.1016/j.scitotenv.2015.08.045.

Moberg, E., E.H. Allison, H.K. Harl, T. Arbow, M. Almaraz, et al. 2021. Combined innovations in public policy, the private sector and culture can drive sustainability transitions in food systems. Nat. Food 2: 282–290. doi: 10.1038/s43016-021-00261-5.

Muhammed, S.E., K. Coleman, L. Wu, V.A. Bell, J.A.C. Davies, et al. 2018. Impact of two centuries of intensive agriculture on soil carbon, nitrogen and phosphorus cycling in the UK. Sci. Total Environ. 634: 1486–1504. doi: 10.1016/j.scitotenv.2018.03.378.

TEEB (The Economics of Ecosystems and Biodiversity). 2018. Measuring what matters in agriculture and food systems: a synthesis of the results and recommendations of TEEB for Agriculture and Food's Scientific and Economic Foundations report. Geneva, Switzerland, UN Environment. http://teebweb.org/our-work/agrifood/reports/measuring-what-matters-synthesis/ (accessed 24 September 2021).

Mylona, K., Maragkoudakis, P., Bock, A., Wollgast, J., Louro Caldeira, S., Ulberth, F., 2016. Delivering on EU Food Safety and Nutrition in 2050 - Future challenges and policy preparedness, EUR 27957. Publications Office of the European Union, Geel. doi: 10.2787/625130.

NCD Risk Factor Collaboration (NCD-RisC). 2016. Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19·2 million participants. Lancet 387(10026): 1377–1396. doi: 10.1016/S0140-6736(16)30054-X.

Nziguheba, G., S. Zingore, J. Kihara, R. Merckx, S. Njoroge, et al. 2016. Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. Nutr. Cycl. Agroecosystems 104(3): 321–340. doi: 10.1007/s10705-015-9729-y.

Nziguheba, G. 2007. Overcoming phosphorus deficiency in soils of Eastern Africa: recent advances and challenges. In: Bationo, A., Waswa, B., Kihara, J., and Kimetu, J., editors, Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht, Netherlands. pp.149–160. doi: 10.1007/978-1-4020-5760-1_13.

O'Neill, B.C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, et al. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42: 169–180. doi: 10.1016/J.GLOENVCHA.2015.01.004.

Ockenden, M.C., M.J. Hollaway, K.J. Beven, A.L. Collins, R. Evans, et al. 2017. Major agricultural changes required to mitigate phosphorus losses under climate change. Nat. Commun. 8: 161. doi: 10.1038/s41467-017-00232-0.

OECD/FAO. 2019. OECD-FAO Agricultural Outlook 2019-2028. OECD Publishing, Paris. doi: 10.1787/agr_outlook-2019-en.

Okumah, M., J. Martin-Ortega, P. Novo, and P.J. Chapman. 2020. Revisiting the determinants of pro-environmental behaviour to inform land management policy: A meta-analytic structural equation model application. Land 9(5): 135. doi: 10.3390/LAND9050135.

Paillard, S., S. Treyer, and B. Dorin, editors. 2014. Agrimonde – Scenarios and Challenges for Feeding the World in 2050. Springer, Dordrecht. doi: 10.1007/978-94-017-8745-1.

Pereira, O.J.R., L.G. Ferreira, F. Pinto, and L. Baumgarten. 2018. Assessing Pasture Degradation in the Brazilian Cerrado Based on the Analysis of MODIS NDVI Time-Series. Remote Sens. 10 (11): 1761. doi: 10.3390/rs10111761.

Poore, J., and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. Science 360(6392): 987–992. doi: 10.1126/science.aaq0216.

Powers, S.M., T.W. Bruulsema, T.P. Burt, N.I. Chan, J.J. Elser, et al. 2016. Long-term accumulation and transport of anthropogenic phosphorus in three river basins. Nat. Geosci. 9: 353–356. doi: 10.1038/ngeo2693.

Pretty, J., C. Toulmin, and S. Williams. 2011. Sustainable intensification in African agriculture. Int. J. Agric. Sustain. 9(1): 5–24. doi: 10.3763/ijas.2010.0583.

Propcom Mai-karfi. 2014. Education and lasting access to fertiliser: how Nigerian smallholders and businesses are prospering together, The Springfield Centre for Business In Development Ltd., Durham, UK . doi: 10.22004/ag.econ.308652.

Ranganathan, J., D. Vennard, R. Waite, B. Lipinski, T. Searchinger, et al. 2016. Shifting Diets for a Sustainable Food Future. Working Paper, Installment 11 of Creating a Sustainable Food Future. Washington D.C., World Resources Institute Working Paper. https://www.wri.org/research/shifting-diets-sustainable-food-future (accessed 24 September 2021).

Ricciardi, V., N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo. 2018. How much of the world's food do smallholders produce? Glob. Food Sec. 17: 64–72. doi: 10.1016/j.gfs.2018.05.002.

de Ridder, M., S. de Jong, J. Polchar, and S. Lingemann. 2012. Risks and Opportunities in the Global Phosphate Rock Market. Robust Strategies in Times of Uncertainty. The Hague Centre for Strategic Studies Report No 17 | 12 | 12. The Hague Centre for. Strateg.ic Studies, The Hague, Netherlands. https://www.phosphorusplatform.eu/images/download/HCSS_17_12_12_Phosphate.pdf (accessed 24 September 2021).

Ripple, W.J., C. Wolf, T.M. Newsome, M. Galetti, M. Alamgir, et al. 2017. World Scientists' Warning to Humanity: A Second Notice. Bioscience 67(12): 1026–1028. doi: 10.1093/biosci/bix125.

Röös, E., G. Carlsson, F. Ferawati, M. Hefni, A. Stephan, et al. 2018. Less meat, more legumes: prospects and challenges in the transition toward sustainable diets in Sweden. Renew. Agric. Food Syst. 35(2): 192–205. doi: 10.1017/S1742170518000443.

Rosa, I.M.D., H.M. Pereira, S. Ferrier, R. Alkemade, L.A. Acosta, et al. 2017. Multiscale scenarios for nature futures. Nat. Ecol. Evol. 1(10): 1416–1419. doi: 10.1038/s41559-017-0273-9.

Rothwell, S.A., D.G. Doody, C. Johnston, K.J. Forber, O. Cencic, et al. 2020. Phosphorus stocks and flows in an intensive livestock dominated food system. Resour. Conserv. Recycl. 163: 105065. doi: 10.1016/j.resconrec.2020.105065.

Rowe, H., PJA. Withers, P. Baas, N.I. Chan, D. Doody, et. al. 2016. Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security. Nutr. Cycl. Agroecosystems 104, 393–412. https://doi.org/10.1007/s10705-015-9726-1.

Roy, E.D., P.D. Richards, L.A. Martinelli, L. Della Coletta, S.R.M. Lins, et al. 2016. The phosphorus cost of agricultural intensification in the tropics. Nat. Plants 2: 16043. doi: 10.1038/nplants.2016.43.

Runge, C.F., B. Senaeur, P.G. Pardey, and M.W. Rosegrant. 2003. Ending Hunger by 2050: Crucial Investments and Policies. International Food Policy Research Institute, Washington, D.C.

Rushton, J. 2015. Anti-microbial Use in Animals: How to Assess the Trade-offs. Zoonoses Public Health 62: 10–21. doi: 10.1111/zph.12193.

Sanchez, P.A., C.A. Palm, and S.W. Buol. 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. Geoderma 114(3–4): 157–185. doi: 10.1016/S0016-7061(03)00040-5.

Sanchez, P.A. 2002. Soil Fertility and Hunger in Africa. Science (5562): 2019–2020. doi: 10.1126/science.1065256.

Schröder, J.J., A.L. Smit, D. Cordell, and A. Rosemarin. 2011. Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. Chemosphere 84(6): 822–831. doi: 10.1016/j.chemosphere.2011.01.065.

Searchinger, T., R. Waite, C. Hanson, J. Ranganathan, and P. Dumas. 2019. Creating a sustainable food future. A Menu of Solutions to Feed Nearly 10 Billion People by 2050. World Resources Institute, Washington D.C., USA.

Seck, P.A., E. Tollens, M.C.S. Wopereis, A. Diagne, and I. Bamba. 2010. Rising trends and variability of rice prices: Threats and opportunities for sub-Saharan Africa. Food Policy 35(5): 403–411. doi: 10.1016/J.FOODPOL.2010.05.003.

Seddon, N., B. Turner, P. Berry, A. Chausson, and C.A.J. Girardin. 2019. Grounding nature-based climate solutions in sound biodiversity science. Nat. Clim. Chang. 9(2): 84–87. doi: 10.1038/s41558-019-0405-0.

Smil, V. 2000. Phosphorus in the Environment: Natural Flows and Human Interferences. Annu. Rev. Energy Environ. 25(1): 53–88. doi: 10.1146/annurev.energy.25.1.53.

Springmann, M., K. Wiebe, D. Mason-D'Croz, T.B. Sulser, M. Rayner, et al. 2018. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet. Heal. 2(10): e451–e461. doi: 10.1016/S2542-5196(18)30206-7.

Suh, S., and S. Yee. 2011. Phosphorus use-efficiency of agriculture and food system in the US. Chemosphere 84(6): 806–813. doi: 10.1016/j.chemosphere.2011.01.051.

Sutton, M.A., A. Bleeker, C.M. Howard, M. Bekunda, M. Grizzetti, et al. 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre of Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Swinburn, B.A., V.I. Kraak, S. Allender, V.J. Atkins, P.I. Baker, et al. 2019. The Global Syndemic of Obesity, Undernutrition, and Climate Change: The Lancet Commission report. Lancet 393(10173): 791–846. doi: 10.1016/S0140-6736(18)32822-8.

Syers, J., A. Johnston, and D. Curtin. 2008. Efficiency of soil and fertilizer phosphorus use: Reconciling changing concepts of soil phosphorus behaviour with agronomic information. FAO Fertilizer and Plant Nutrition Bulletin 18. FAO, Rome, Italy. http://www.fao.org/3/a1595e/a1595e00.pdf (accessed 24 September 2021).

Tadasse, G., B. Algieri, M. Kalkuhl, and J. von Braun. 2014. Drivers and triggers of international food price spikes and volatility. Food Policy 27: 117–128. doi: 10.1016/j.foodpol.2013.08.014.

The National Intelligence Council (USA). 2017. Global Trends: Paradox of Progress. Office of the Director of the National Intelligence Council, USA.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108(50): 20260–20264. doi: 10.1073/pnas.1116437108.

Tonini, D., H.G.M. Saveyn, and D. Huygens. 2019. Environmental and health co-benefits for advanced phosphorus recovery. Nat. Sustain. 2(11): 1051–1061. doi: 10.1038/s41893-019-0416-x.

Udert, K.M., B. Etter, and T. Gounden. 2016. Promoting Sanitation in South Africa through Nutrient Recovery from Urine. GAIA - Ecol. Perspect. Sci. Soc. 25(3): 194–196. doi: 10.14512/gaia.25.3.12.

Udo, B. 2013. Nigeria saves N776 billion from fertiliser fraudsters in one year – Minister. Premium Times. https://www.premiumtimesng.com/news/150135-nigeria-saves-n776-billion-fertiliser-fraudsters-one-year-minister.html (accessed 26 January 2019).

UK Ministry of Defence. 2018. Global Strategic Trends - The Future Starts Today. Sixth Edition. Development, Concepts and Doctrine Centre, Ministry of Defence, London, UK.

United Nations, 2021. United Nations Food Systems Summit 2021 https://www.un.org/en/food-systems-summit (accessed 4 August 2021).
Vanlauwe, B., and K. Giller. 2006. Popular myths around soil fertility management in sub-Saharan Africa. Agric. Ecosyst. Environ. 116(1–2): 34–46. doi: 10.1016/j.agee.2006.03.016.

van der Velde, M., C. Folberth, J. Balkovič, P. Ciais, S. Fritz, et al. 2014. African crop yield reductions due to increasingly unbalanced Nitrogen and Phosphorus consumption. Glob. Chang. Biol. 20(4): 1278–1288. doi: 10.1111/gcb.12481.

Walker, W., M. Haasnoot, and J. Kwakkel. 2013. Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. Sustainability 5(3): 955–979. doi: 10.3390/su5030955.

Webb, P., T.G. Benton, J. Beddington, D. Flynn, N.M. Kelly, et al. 2020. The urgency of food system transformation is now irrefutable. Nat. Food 1: 584–585. doi: 10.1038/s43016-020-00161-0.

Weber, O., J. Delince, Y. Duan, L. Maene, T. McDaniels, et al. 2014. Trade and Finance as Cross-Cutting Issues in the Global Phosphate and Fertilizer Market. In: Scholz, R.W., Roy, A.H., Brand, F.S., Hellums, D.T., and Ulrich, A.E., editors, Sustainable Phosphorus Management. Springer, Dordrecht Netherlands. pp.275–294. doi: 10.1007/978-94-007-7250-2_7.

West, P.C., J.S. Gerber, P.M. Engstrom, N.D. Mueller, K.A. Brauman, et al. 2014. Leverage points for improving global food security and the environment. Science 345(6194): 325–328. doi: 10.1126/science.1246067.

Westhoek, H., J.P. Lesschen, A. Leip, T. Rood, S. Wagner, et al. 2015. Nitrogen on the Table: The influence of food choices on nitrogen emissions and the European environment. (European Nitrogen Assessment Special Report on Nitrogen and Food). Centre for Ecology & Hydrology, Edinburgh, UK.

WHO/UNICEF JMP (Joint Monitoring Programme). 2017. Global data on Water Supply, Sanitation and Hygiene (WASH). https://washdata.org/monitoring/sanitation.

WHO. 2003. Diet, Nutrition and the Prevention of Chronic Diseases. Report of a Joint WHO/FAO Expert Consultation. WHO Technical Report Series 916. WHO, Geneva, Switzerland.

Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, et al. 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393(10170): 447–492. doi: 10.1016/S0140-6736(18)31788-4.

Withers, P.J.A., K.G. Forber, C. Lyon, S. Rothwell, D.G. Doody, et al. 2020. Towards resolving the phosphorus chaos created by food systems. Ambio 49(5): 1076–1089. doi: 10.1007/s13280-019-01255-1.

Withers, P.J.A., M. Rodrigues, A. Soltangheisi, T.S. De Carvalho, L.R.G. Guilherme, et al. 2018. Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci. Rep. 8: 2537. doi: 10.1038/s41598-018-20887-z.

Withers, P.J.A., C. Neal, H.P. Jarvie, D.G. Doody, P.J.A. Withers, et al. 2014a. Agriculture and Eutrophication: Where Do We Go from Here? Sustainability 6(9): 5853–5875. doi: 10.3390/su6095853.

Withers, P.J.A., R. Sylvester-Bradley, D.L. Jones, J.R. Healey, and P.J. Talboys. 2014b. Feed the Crop Not the Soil: Rethinking Phosphorus Management in the Food Chain. Environmental Science & Technology 48(12): 6523–6530. doi: 10.1021/es501670j.

World Economic Forum. 2017. Shaping the Future of Global Food Systems: A Scenarios Analysis. World Economic Forum and Deloitte. https://www.weforum.org/whitepapers/shaping-the-future-of-global-food-systems-a-scenarios-analysis (accessed 24 September 2021).

WRI. 2016. Protein Scorecard. Washington D.C., World Resources. Institute. https://wriorg.s3.amazonaws.com/s3fs-public/WRI_Protein_Scorecard_final_1.jpg (accessed 8 July 2021).

Zhang, Y., A.L. Collins, P.J. Johnes, and J.I. Jones. 2017. Projected impacts of increased uptake of source control mitigation measures on agricultural diffuse pollution emissions to water and air. Land Use Policy 62: 185–201. doi: 10.1016/J.LANDUSEPOL.2016.12.017.