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Towards net-zero phosphorus cities

Geneviève S. Metson[1]✉, Will J. Brownlie[2,3] and Bryan M. Spears[3]

Cities are central to improving natural resource management globally. Instead of reinventing the wheel for each interlinked sustainability priority, we suggest synergising with, and learning from existing net-zero carbon initiatives to explicitly tackle another vital element: phosphorus. To achieve net-zero phosphorus actors must work together to (1) minimise loss flows out of the city, (2) maximise recycling flows from the city to agricultural lands, and (3) minimise the need for phosphorus in food production.

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CALL FOR CITIES AS BRIGHT SPOTS OF RESOURCE MANAGEMENT

With over 700 cities committed[1] to achieving net-zero carbon goals by 2050, urban areas have become central in combatting climate change and achieving carbon sustainability[2]. Just as for carbon, urban populations are the motor driving the anthropogenic phosphorus cycle through their demand for phosphorus-intensive agricultural production. Yet, urban phosphorus management is currently insufficient and locked into a pattern of high phosphorus consumption and high waste. Cities receive phosphorus as food imports and concentrate emissions of phosphorus from waste/residue streams to the aquatic environment (Fig. 1a). A lack of coordinated efforts within and across cities place city dwellers at risk of food price fluctuations and water pollution associated with poor phosphorus management.

Here, we propose the 'net-zero phosphorus cities' concept and highlight the key flows that must be addressed to connect urban centres within circular phosphorus economies designed to deliver benefits that resonate far beyond individual city boundaries. Inter-city coordinated action on sustainable phosphorus management is an opportunity to deliver on global sustainability ambitions, including multiple UN Sustainable Development Goals (SDGs) related to food security and water pollution through more sustainable production and consumption (Table 1)[3,4]. We present opportunities to build on existing plans and frameworks put in place by cities within net-zero carbon initiatives, and in doing so embrace a systems approach deemed necessary for a transition to sustainable cities[5]. City mayors and municipal entities (e.g., departments tasked with city planning, green infrastructure, solid and liquid waste management, and public procurement) can use the proposed framework to become leaders in urban phosphorus stewardship.

THE GLOBAL PHOSPHORUS CHALLENGE

Phosphorus is an essential component of fertilisers and is part of all organic matter. Globally, around 85% of marketable mined phosphorus is processed to make mineral phosphorus fertilisers to satisfy crop demands; a further 10% is consumed in animal feed supplements, while the remaining 5% is used in diverse chemical industry processes including detergent and battery production, and metallurgy[6]. Phosphorus is geopolitically scarce; 85% of world phosphate rock reserves are in just five countries, notably Morocco and Western-Sahara, China, and Russia[7]. Export tariffs and bans (e.g., China in 2008 and 2022[8]) and wars (e.g., Russia's invasion of Ukraine affecting energy and subsequently fertiliser prices[9]), in addition to physical and logistical constraints, affect phosphorus resource availability, which in turn contributes to food price fluctuations. Long-term reliable access to phosphorus (which is stored in rocks, organic materials, and soils) is an essential part of a sustainable food system. All farmers require phosphorus, although some farmers require more phosphorus than others to achieve desirable yields because of local soil characteristics (e.g., those high in iron, aluminium, or calcium, and/or with a history of under-fertilisation), and not all farmers have the same physical or financial access to mineral phosphorus[10,11]. Over the last 60 years, the average amount of mineral phosphorus fertiliser required to produce food for one person, over one year, has risen by 38%, mainly due to the growing consumption of animal products[12]. For instance, between 1961 and 2013 the amount of phosphorus lost to support the average Chinese diet increased from <1 kg to ~5 kg of phosphorus per year per person[13]. Urban residents often have higher meat consumption and higher food waste production than their rural counterparts because of higher income, making them central in efforts to decouple wealth from unsustainable consumption patterns. Increases in animal product consumption, and changes in farm practices, have not only increased the use of mineral phosphorus fertilisers but also increased net losses of phosphorus to soil and water along the food production chain.

Currently, ~14 million tonnes of phosphorus are lost to global aquatic ecosystems every year[14] causing a multitude of problems. Phosphorus is lost through runoff and erosion from fields and areas with livestock, as well as from human settlements with insufficient capacity to treat organic waste (especially human excreta and other wastewaters). Just as phosphorus and nitrogen can be used to boost crop growth, an excess of these nutrients in waterways (called *eutrophication*) can boost aquatic plant growth, which can cause problematic algal blooms and associated bottom-water hypoxia[15]. Eutrophication is estimated to cost the US economy over 2.2 billion dollars each year in losses associated with, for example, a reduction in biodiversity, recreational opportunities, and lakefront property value[16]. In addition, algal blooms in eutrophic waters are more likely to be dominated by cyanobacteria which are harmful to humans and animals. In 2014, the city of Toledo in the U.S. temporarily lost access to all drinking water because of cyanobacteria contamination[17]. The presence of hypoxic zones in lakes and coastal waters (prominent examples include the Gulf of Mexico[18] and the Baltic Sea[19]) reduces fish and

[1]Ecological and Environmental Modelling Division, IFM, Linköping University, Linköping, Sweden. [2]The University of Edinburgh, Edinburgh, UK. [3]UK Centre for Ecology and Hydrology, Edinburgh, UK. ✉email: genevieve.metson@liu.se

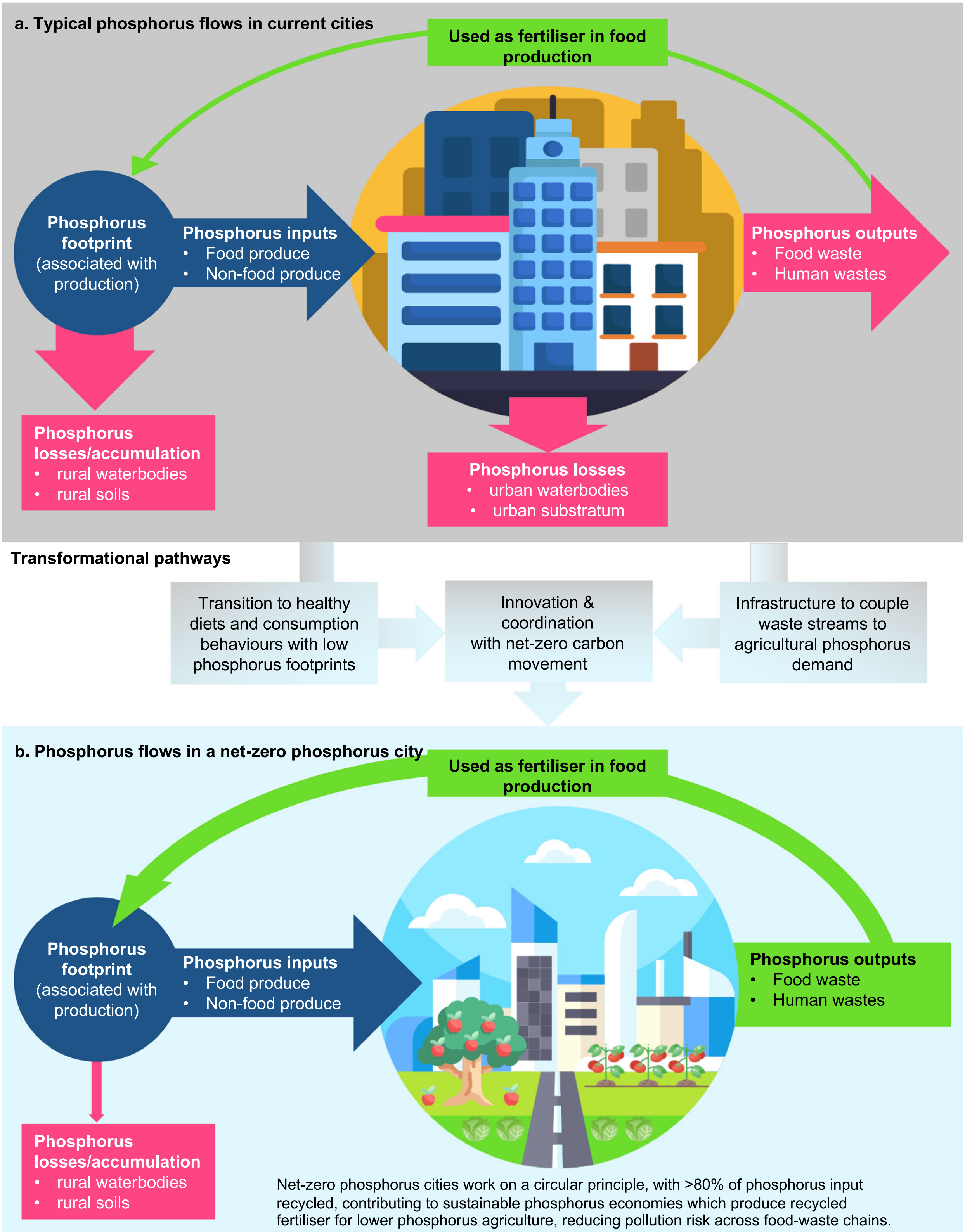

Fig. 1 Transformation to a net-zero phosphorus city. Typical phosphorus flows in cities currently depicted in (**a**), in contrast to a net-zero phosphorus city depicted in (**b**), and the key transformational pathways to transition to more sustainable urban centres between the two panels. These include (i) minimising unproductive phosphorus outputs from the city to protect waterways, (ii) developing infrastructure to couple waste streams to agricultural phosphorus demand, and (iii) transitioning to healthy diets and consumption behaviours with low phosphorus footprints (the phosphorus footprint is here defined as the phosphorus in fertiliser required to produce a unit of a food/non-food product). This should be done by developing a coordinated approach with the net-zero carbon movement, to maximise synergies and innovation with an experimental approach to adapt to local conditions. This figure has been designed using resources from Flaticon.com.

Table 1. Link between sustainable development goals (SDG) targets and phosphorus (P) management.

SDG	Target	Target link to P
2 Zero hunger	2.3 double the agricultural productivity and incomes of small-scale food producers… 2.4 ensure sustainable food production systems and implement resilient agricultural practices	Productive agriculture requires access to affordable and renewable P fertilisers.
3 Good health and well-being	3.9 substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Requires limiting P and nitrogen induced toxic algal blooms.
6 Clean water and sanitation	6.2 achieve access to adequate and equitable sanitation and hygiene 6.3 … halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	Human excreta and other wastewater contain P (notably cleaning water where P has not been banned in detergents) which when untreated can enter waterways and cause eutrophication. Orthophosphate is also used in some locations to reduce lead concentrations in drinking water pipes, although this is not always effective[77].
7 Affordable and Clean Energy	7.2 increase substantially the share of renewable energy in the global energy mix	Organic residue streams can be used as a form of renewable energy, but they also contain P that can be reused for food production.
9 Industry, innovation, and infrastructure	9.1 Develop quality, reliable, sustainable, and resilient infrastructure… 9.4 upgrade infrastructure and retrofit industries to make them sustainable	All organic residues (food, landscaping/gardening, and human and animal excreta) contain P. Infrastructure for residue collection and processing influences the capacity for reuse of recycled P in agriculture. P in unavoidable organic residue streams should be transported to where P can be used in food production.
11 Sustainable cities and communities	11.6 …reduce the adverse per capita environmental impact of cities, including by paying special attention to waste management 11.7 …provide universal access to safe, inclusive, and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	See SDG 9 on organic waste and SDG 12 on resource use to produce food. All plants require P to grow. What type of green space is prioritised (e.g. urban agriculture vs trees), fertilisation practices (type and amount of P applied), and watering practices affect P demand, recycling, and losses.
12 Sustainable consumption and production	12.2 …achieve the sustainable management and efficient use of natural resources 12.3 …halve per capita global food waste at the retail and consumer levels 12. 5 …substantially reduce waste generation 12.7 Promote public procurement practices that are sustainable 12.8 …ensure that people everywhere have the relevant information and awareness	All food production requires P. It can come from mined or recycled sources and can be used with varying degrees of efficiency. Animal products require much more P per calorie than plant foods. Agricultural and food waste contains P.
13 Climate action	13. 1 Strengthen resilience and adaptive capacity to climate-related hazards	Climate change will increase the risk of negative effects of eutrophication (losses from land and sensitivity of water bodies). Eutrophic water bodies can contribute to climate change[78]. Reduced use of mineral P fertilisers and matching crop needs reduces GHGs[79].
14 Life below water and 15 Life on land	14.1 prevent and significantly reduce marine pollution of all kinds, including … nutrient pollution 15.1 ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems	Loss of terrestrial P to oceans and inland waters can cause eutrophication, harmful algal blooms, and anoxic zones radically transforming these aquatic systems.

shellfish production, affecting livelihoods, food security, and ecological integrity. To avoid further damages, losses of phosphorus (and nitrogen) need to be addressed along the entire food production chain[20,21], and treating phosphorus-containing residues from cities is a key piece of the puzzle.

Simultaneous and urgent action is required to address both issues of phosphorus scarcity for food security and phosphorus excesses for water quality[3,22]. More sustainable phosphorus management options[23,24] fall into three broad categories, (1) increase efficiency and decrease waste/losses throughout the food system, (2) increase recycling of organic waste high in phosphorus (e.g., excreta and food and crop waste), and (3) decrease demand (e.g., change human diets, animal diets and reliance on particular species, and plant cultivars). The technology and know-how to make significant progress toward more sustainable phosphorus use in cities are already available[25,26]. However, a lack of awareness, acceptance, and governance currently holds back the uptake of phosphorus recycling approaches and effective use throughout the food system.

CARBON VS PHOSPHORUS CYCLING AND THE ROLE OF CITIES

The momentum gained on net-zero carbon initiatives may offer an opportunity to deliver also on sustainable phosphorus management. However, fundamental differences exist between 'net-zero' concepts for phosphorus and carbon because these elements cycle differently.

1. Whilst major pathways for problematic anthropogenic carbon emissions accumulate in the atmosphere, those for phosphorus flow from land to aquatic ecosystems. For carbon, local actions that reduce atmospheric emissions can have a large global impact through addressing the drivers of

climate change. For instance, decarbonizing transportation and fuel consumption in any city's territory is beneficial to the entire planet. For phosphorus, regional actions including reducing emissions from wastewater to aquatic ecosystems, are required to deliver local impacts including the provision of clean drinking water. This is because the effects of carbon emissions are moderated by atmospheric processes, and the benefits of reduction are on global climate systems. For phosphorus, the impacts of emissions are moderated by the sensitivity of the receiving lake, reservoir, river, or coastal ecosystem, and the benefits of emissions reductions appear along the transport pathway. For carbon, local actions anywhere are impactful, which means that some cap-and-trade or offset system could be meaningful in principle. Global, or even national, cap-and-trade or offset schemes are likely ineffective for phosphorus pollution. Coordinated actions among all phosphorus emitters within a watershed, including cities, are needed to protect the water quality of receiving water bodies. To address the food security angle of phosphorus management, even more coordination is needed. Global actions, such as reducing excess fertilizer demand, are likely required for meaningful local impacts, for example, ensuring access to affordable fertilisers to increase yields[10,27].

2. Atmospheric carbon emissions, in the context of net-zero, are a 'pollutant' to reduce, whilst phosphorus is a resource to be better managed and conserved. The largest urban sources of carbon emissions are related to energy, meaning that substituting fossil fuels for renewable energy achieves a large part of a net-zero target. There is no substitute for phosphorus; it is an integral part of all organic matter which means it is impossible to have zero use on farms and zero outputs as residues from cities. For carbon, the discussion can (at least, theoretically) go from net-zero to zero. For phosphorus, the discussion must be around net-zero, where unavoidable urban and rural outputs are recycled back to where they are needed. Cities cannot only be concerned with reducing phosphorus emissions, they must also engage meaningfully with the food security angle of the phosphorus challenge. This means taking actions that will increase circularity, returning urban phosphorus 'waste' to food production, and decrease demand throughout the food system by reducing consumption and waste of products with a high phosphorus-demand.
3. City governments may feel they have less power to affect phosphorus than carbon. Although all sectors that must be mobilised to achieve net-zero carbon cities also touch phosphorus (Tables 1 and 2), the relative importance of each sector for phosphorus management is different. This means that different departments within city governments may need to be more mobilized, or different actors brought in to create meaningful change. For carbon, city governments often have some centralised power over sectors that can result in drastic emission reductions. For example, re-designing cities to limit cars and favour collective and active transport[28] is in the purview of a small number of entities, even if it is individual residents that decide to drive or walk. Similarly, a city (or a public company) may be an energy provider (i.e., electricity or gas), meaning that they have power to change production methods, create different building codes or purchase orders, and decrease waste in a given infrastructure network. For phosphorus, wastewater, the management of green spaces (e.g., lawns, parkland, and agricultural lands within a city), and organic solid wastes are relatively more important than for carbon[29]. Changes to the infrastructure around these issues, in particular wastewater, can require long-term planning and centralized investment led by city governments. Importantly, capturing phosphorus before it enters a local waterway via recovery in wastewater, green spaces, or solid waste does not ensure desirable outcomes for food security or water quality. Recovery needs to be done in tandem with policies and practices that ensure it is recycled to produce food. Similarly, and as mentioned already in point two, coordinated actions are required across a watershed to deliver water quality benefits. City action plans need to embrace the fact that transformation must occur on multiple fronts, beyond administrative city boundaries, to ensure coupled carbon and phosphorus net-zero goals can be set, and, met[30].

The concept of urban metabolism is helpful to describe and quantify how cities simultaneously concentrate resource flows (e.g., carbon, phosphorus, nitrogen, and others) on the landscape, whilst also having a large resource footprint beyond their physical boundaries[31–33]. One can track the amounts of resources entering a city, transformed within its boundary, and exported. In addition, one can account for the indirect use of energy or resources associated with direct flows, including, energy consumption, environmental footprints, and life-cycle assessments[34]. For carbon, there is a well-established greenhouse gas inventory framework[35], but cities do not always include both emissions within and outside their boundaries. This makes comparisons between cities difficult and can obfuscate real efforts through greenwashing[36,37].

In addition to describing flows, it is essential to consider networks of drivers (both social and natural drivers) for resource flows to find effective governance solutions[31,38,39]. Taking a systems approach is necessary to design urban social and physical infrastructures that account for how urban environments are dependent upon, and affect, multiple resources at multiple scales[40]. This is, in part, why we advocate for phosphorus, building on existing net-zero carbon approaches which are already integrated into diverse planning schemes.

DEFINING 'NET-ZERO PHOSPHORUS' FOR CITIES

The 'net-zero phosphorus city' concept aims to improve phosphorus sustainability across product value-chains and underlying social norms. In practice, a net-zero phosphorus city will minimise inputs and outputs (particularly losses) of phosphorus from the city, recycle those outputs that cannot be eliminated, and support the efficient use of phosphorus, including the use of recycled phosphorus fertilisers on farms (Fig. 1b). In the context of the net-zero phosphorus concept, a city is defined as the administrative boundaries of densely populated areas, as we envision the framework being used by mayors and their municipal staff. Instead of reinventing the wheel for each interlinked sustainability priority, we suggest an expansion and alteration of existing net-zero carbon initiatives to explicitly tackle phosphorus. The power of net-zero carbon lies in the coordinated efforts of many cities which is exemplified by an urban session at COP 26[41]. Phosphorus management requires the same concerted effort, where cities learn from each other and collectively use their influence, and capital, to increase phosphorus recycling and reduce pollution along the food production and consumption chain.

We envision an iterative process where phosphorus flows are carefully monitored to allow for adaptive management. As mentioned in the previous section, mapping the resource use impacts of a city's consumption patterns is complex due to their embeddedness within larger-scale infrastructural, social, and ecological systems[42]. To be effective, all net-zero phosphorus cities need a consistent monitoring approach to collect accurate and comparable data on phosphorus flows. Data should include the phosphorus content and footprint of food and non-food products, and phosphorus residues flowing in and out of cities. Urban supply chain footprinting would allow for the identification of dependencies and key interactions, for example, import

Table 2. Questions to ensure urban decarbonisation includes phosphorus (P) sustainability as a way of meeting multiple Sustainable Development Goals (SDG).

SDG	City-specific questions to harness net-zero P potential in the context of existing net-zero carbon goals, planning documents, and implementation
2 Zero hunger	• see SDG 6 and SDG 11 questions for ensuring the supply of fertilisers in this table • see SDG 11 and SDG 12 questions for altering demand and thus essential to meeting these targets in this table
3 Good health and well-being	• See SDG 14 and SDG 15 questions in this table
6 Clean water and sanitation	• Do new climate-smart building codes include provisions for source-separated sanitation? • Does sanitation collection and treatment infrastructure allow for the safe reuse of water and solids? • Does sanitation treatment infrastructure account for the fact that both P and nitrogen need management so that nutrient ratios minimize environmental damage and facilitate agricultural reuse? • Are planned green and decentralised infrastructure(s) for organic waste management facilities (incl. sanitation) desirable for communities to have close to home? Also related to target 6.b • Are plans in place to learn across cities, especially across income levels? Also related to target 6.a
7 Affordable and Clean Energy	• Are green energy systems using organic materials designed to recover nutrients? • Are partnerships in place with other cities to learn about how to best valorise organic matter for more than only energy production? Also touches target 7.a
9 Industry, innovation, and infrastructure	• Is there a fossil-free transport plan to collect organic waste in the city and export the recycled fertilisers to rural farmers? • See SDG 6, SDG 7, and SDG 11 questions on energy and sanitation infrastructure in this table
11 Sustainable cities and communities	• Are healthy and plant-based products available and promoted in grocery stores, cafeterias, restaurants and at cultural events? • Are food and green/landscaping wastes collected separately? • Are contracts in place with transformers and farmers to safely utilise the source-separated organic wastes generated from the city (target 11.a)? Are there clear fertilisation plans for municipal and private green infrastructure (e.g. gardens, green roofs, parks, trees) that favour efficient P use, recycled P use, and P retention?
12 Sustainable consumption and production	• Do the climate-friendly foods promoted and procured ∘ stipulate a nutrient use efficiency requirement and ∘ encourage P reuse from urban organic waste streams when appropriate? • Do public information campaigns for healthy eating and lowering food waste talk about the multiple benefits of this transition, including phosphorus? • Do public information campaigns on sustainable food include the need to safely reuse organic wastes, including human excreta?
13 Climate action	See questions across other SDGs in this table as the point is to integrate P into existing climate mitigation and adaptation plans
14 Life below water and 15 Life on land	• Is there a water quality monitoring and intervention scheme in place that makes sure that the sanitation (SDG 6) and organic waste (SDG 11) systems put in place working and thus not negatively contributing to aquatic losses of P from land to water? • Is there a water quality monitoring and intervention scheme in place that makes sure that diffuse sources of P from green infrastructure (SDG 11) and other land uses are not negatively contributing to aquatic losses of P from land to water?

It is important to note that addressing a specific P angle for a given SDG target has implications for how an actor can address other targets (see Table 1 for P link to specific targets). Looking at 'upstream' solutions which reduce and source separate wastes, or decrease demand for P, will have more systemic effects for sustainable management than solutions that only look at collecting and treating waste that contains P.

pathways for fertilisers and loss pathways for products that incur a high phosphorus footprint.

The net-zero phosphorus concept embraces the idea that solutions need to account for the specific social, ecological, and technological context of a city[43,44]. Therefore 'placed-based' experimentation and collaboration will be necessary to achieve transformational goals. Understanding city-specific motivators and barriers to current phosphorus use and recycling are necessary to meet sanitation and food production objectives[45]. These may not be named 'phosphorus issues', but through a systems perspective one can identify how phosphorus is linked to existing priorities (e.g., Tables 1 and 2) and challenges. For example, poor road infrastructure may limit the capacity to move organic waste to recycle phosphorus[46]. We draw on lessons not only from the net-zero carbon movement but also on cities as living labs[47], where investments in physical and social infrastructure are dynamic and reflexive. Importantly, experiments should be designed as learning spaces. To fully utilise the 'power' of the city to affect change beyond its borders, individual citizens need to be engaged in ways that affect social norms and behaviours on a wide spectrum of issues. To do so, learning must be explicitly and intentionally designed in experimental settings[48].

In summary, the net-zero city concept can be used to motivate strategies designed to better integrate phosphorus management within climate change adaptation and mitigation plans[49]. Doing so will deliver wider benefits including supporting circular economies[50] whilst contributing towards achieving multiple SDGs. Below we highlight the three major phosphorus flows that a net-zero phosphorus city would transform.

Minimise loss flows out of the city

Net-zero phosphorus cities would identify and control existing residue streams to reduce losses and deliver multiple benefits associated with ecosystem restoration. Managing these flows falls within the first of the three categories to address the phosphorus challenge: *increase efficiency and decrease waste/losses*. Actions may be centred on impacted ecosystems, accounting for the first difference between carbon and phosphorus cycling mentioned previously. For example, improving water quality in small urban waters (e.g., parkland ponds) to reduce human health risks for users, create new eco-tourism jobs, or increase shoreline property values, may be achieved through sub-urban groups targeting local emissions reduction actions. However, ensuring the delivery of emissions reduction programmes for transboundary lakes or marine ecosystems, for example, to support food production or freshwater and marine biodiversity protection, requires coordinated actions across multiple cities, and countries within multilateral Strategic Action Programmes, or conventions[15].

Globally, human excreta and other organic residues contain about 3.3 Mt and 4.7 Mt phosphorus year^{-1}, respectively, of which 1.1 Mt is recycled and the remainder is lost to landfill or discharged to surface waters[14]. With most people located in cities, a large proportion of these losses are concentrated in urban areas. In low-income countries, only 8% of wastewater undergoes treatment, supporting the often-cited approximation that, globally, over 80% of all wastewater is discharged without treatment[51]. Phosphorus discharge to rivers is likely to increase by 70% by 2050 without concerted efforts from global cities to treat human excreta[52].

Up-scaling urban actions to deliver emissions reduction from local to transboundary scales is challenging. A net-zero phosphorus cities initiative may help to support coordination and collaboration across borders required to deliver on some of the world's most challenging ecosystem restoration programmes. For example, the establishment of the International Commission for the Protection of the Danube River recognises that the Danube River carries waste from 27 cities on its path to the Black Sea. International cooperation has been vital in achieving reductions in urban wastewater and agricultural phosphorus discharges to the Black Sea, although further coordinated efforts are necessary to ensure ecosystem protection[53].

Maximise recycling flows from the city to agricultural lands

A net-zero phosphorus city must not only collect concentrated phosphorus waste but also ensure productive reuse. Managing these flows falls within the second of the three categories to address the phosphorus challenge: *increase recycling of organic waste high in phosphorus*. Closing the phosphorus cycle requires linking urban areas to agricultural land outside cities, embracing the second difference between carbon and phosphorus cycling – phosphorus cannot be viewed as a pollutant to decrease but as a resource. Regional city collaborations could facilitate coordinated reuse to match agricultural needs, and global net-zero collaborations could provide an opportunity to learn from others in terms of technology implementation and mechanisms for social acceptability.

Instead of discharging phosphorus to waterways, ensuring the safe, and source-separated, collection of organic residue streams is necessary. This would involve changes in sanitation infrastructure, from toilet design to treatment technologies. In addition, unavoidable food and landscaping residues should be diverted from landfills and recycled. Many cities are located within agricultural regions where phosphorus derived from urban organic residues could be effectively recycled[54,55]. Around 50% of human urine in 56 of the world's largest cities would need to travel less than 50 km to contribute to food production[54]. For Beijing (the 8th largest city in the world), 95% of the phosphorus in human urine could be recycled within 21 km. Key barriers, here, include insufficient transport logistics and ensuring market opportunities for fertilisers derived from urban organic residues[56,57], in a fertiliser market dominated by mineral-derived fertilisers. The economic value of recycled fertilisers can be maximised by selecting methods to process organic materials that produce additional co-benefits, such as renewable energy from biogas production and recovery of other nutrients[58]. Currently, examples of small-scale biodigester programmes can be found in more than 50 countries across Africa, Asia and South America, as a way of advancing agricultural productivity, renewable energy use, and residue management[59].

There is no 'one solution fits all' for the treatment technologies or recycling arrangements for cities; experimentation and testing will be required. Importantly, concerns about safety related to the re-use of phosphorus from urban organic residues, in particular human excreta, remain a barrier in many places. Multiple waste treatment technologies are available that address human health concerns and are appropriate for upscaling[60]. Citizen participation and education through the expansion of phosphorus-sensitive urban green spaces (e.g., community gardens properly using recycled phosphorus), and climate-smart buildings with phosphorus recovery sanitation, could help influence consumer preferences for phosphorus management in imported food and alternative waste infrastructure.

Minimise losses before food flows into the city

Net-zero phosphorus cities would accelerate the implementation of programmes that minimise the need for phosphorus in food production and support environmentally and socially sustainable farming practices globally. Managing these flows falls within the third of the three categories to address the phosphorus challenge: *decrease demand (change human diets, animal diets and reliance on particular species, and plant cultivars)*, but also supports effective actions in the two other categories. As powerhouses of consumption cities drive food systems through the sum of individual, company, and community choices. From product selection to acceptable production methods, these choices have an impact on phosphorus use. Here cross-city collaborations would be a space for peer-to-peer learning on how to effectively facilitate behaviour change for residents and companies within cities to reduce upstream losses of phosphorus. This pertains to the third difference between carbon and phosphorus cycling – that city governments must engage with sectors where they have less centralized power, and thus where a systems approach to coordination will be needed.

Supporting low-animal product diets is an essential action to transforming the phosphorus cycle, even if it is challenging[61]. For example, if by 2030 Beijing residents adopted a healthy low-meat diet, as recommended in the EAT-Lancet report, losses of phosphorus related to supplying the city with food could be reduced by over 80%. If residents, in addition to eating less meat, consumed only products produced using phosphorus efficient practices (e.g., a 50% reduction in fertiliser, crop, and food losses along the food chain) then, overall, three times less phosphorus would be released to the environment. More specifically, food production to support Beijing's population today releases food 81 Gg of P (multiplying the phosphorus footprint per capita in China[13] and the population in Beijing[62]); but this would be reduced to 30 Gg of phosphorus released to produce food for the city in 2030 despite population growth (calculated by matching EAT-Lancet food category amounts per capita as phosphorus[63] to phosphorus footprint per food category in China[13] and halving these amounts, and then multiplying by projected 2030 city population[64]).

Changing food purchasing and consumption behaviours (as well as waste behaviours) at the individual level is extremely challenging as it is a habitual behaviour that is also culturally, socially, and financially embedded[65–67]. Still, cultural norms have changed and as such can, and will, change again. For example, and in relation to carbon cycling, holiday air travel in Sweden went from being considered a luxury, to fairly recently being viewed as an integral part of mobility, to now being disrupted by holidays that stay on the ground due to consumer concerns over climate change[68].

Experiential learning[69] (learning by doing and being as opposed to increasing knowledge) can support resident behaviour changes. Instead of being told to eat less meat, people should experience nutritious and tasty low-animal product meals and be part of creating these meals. Registration for catered city events, including conferences and festivals, could specify catering requirements which put environmentally friendly meals front and centre, as well as alternative sanitation facilities. Similarly, public procurement and meal preparation for schools, hospitals, and other government-supported institutions could increase exposure/uptake of foods that support diets with low phosphorus footprints, reduced food waste, and organic waste recycling. Menus can be co-created with users and can be part of larger sustainability initiatives and living labs. Community gardens and other forms of urban agriculture may also be a fruitful space for learning and experimentation with regard to nutrient cycling and sustainable food production[70–72].

Overall, urban purchasing should support farmers who produce food with a low phosphorus footprint and utilise recycled phosphorus products in ways that minimise damage to ecosystems and optimise fertiliser use to reduce reliance on mined sources. Collecting data on human activity and preference will be key to re-adjusting behaviour-change campaigns and technology options in the city and provide feedback to food producers about acceptance related to urban-derived fertilisers.

WHERE DO WE GO FROM HERE?

The role of cities in multi-level governance has been highlighted in plans for climate change mitigation[73], and phosphorus sustainability[46]. However, fully leveraging the power of what constitutes a city is an ongoing academic and practical challenge. Although cities concentrate resource flows on the landscape and represent a powerhouse of consumption, and thus resource use outside of city boundaries, cities are not a singular entity. They encompass a collection of individual resident and company decisions, while also remaining dependent on the individual decisions of producers outside the city, and regional and national policies and plans. Given the pressing nature of the climate crisis, the phosphorus challenge, and other crossed planetary boundaries[74], urgent action is required to test how cities can act to meet local and global goals. For example, the Our Phosphorus Futures Report calls for governments to consider the '50:50:50' Goal; a 50% reduction in global phosphorus pollution and a 50% increase in the recycling of phosphorus lost in residues and wastes, by 2050[22].

'Green shoots' of progress for phosphorus sustainability exist in some cities but are siloed to a particular issue. For instance, national mandates for phosphorus recovery from wastewater treatment plants over a certain size in Germany, Switzerland, and Austria are enabling many cities to invest in recovery technologies from incinerated sewage ash[75]. Many states in the U.S. have banned the use of phosphorus fertilisers on lawns, which has helped cities reduce losses to local waterbodies[29]. In isolation, such measures will fail to protect waterbodies sufficiently, and importantly do not ensure food systems are more phosphorus secure.

Transforming cities to net-zero phosphorus will require nothing short of an overhaul of sanitation systems, the relationship of cities to the hinterlands that produce their food, and how residents view their actions as consumers and infrastructure users. We call for mayors to take bold actions by adding a phosphorus lens to the momentum they are already creating to tackle urban and global sustainability challenges through net-zero carbon initiatives and SDG reporting schemes. We suggest they;

1. Review existing plans to explicitly identify areas of overlap with phosphorus (as shown in Table 2),
2. Create specific phosphorus performance indicators that can be monitored for each of these overlaps,
3. Develop the capacity to monitor these indicators because sustainable transformation is an iterative process and monitoring to course-correct is essential,
4. Enact policy changes and on-the-ground experimentation to re-invent cities as producers of sustainable phosphorus fertilisers and conscientious circular economy consumers.

By adding a net-zero phosphorus approach to their endeavours, cities will be better able to ensure residents have access to affordable and reliable food and clean waterways, and the benefits that these deliver.

The United Nations Framework Convention on Climate Change is pioneering the 'Race to Zero'[76] global campaign to rally leadership and support from businesses, cities, regions and investors to achieve net-zero carbon emissions by 2050. Currently, over 1000 cities, 5000 businesses, 400 investors and 1000 education institutions have joined this alliance, covering nearly 25% of global CO_2 emissions and over 50% of gross domestic production. A similar campaign could be used to establish a net-zero phosphorus cities network. This would support coordinated actions and knowledge exchange between cities and the diverse actors that are required to improve urban phosphorus sustainability and achieve relevant SDGs. We call for action, not only from individual cities and mayors, but also for similar collaboration, perhaps led by a relevant United Nations body, to establish a special task force on net-zero phosphorus for cities, to coordinate such a network, and to ensure priority actions align with SDG targets (Tables 1 and 2).

DATA AVAILABILITY

The authors declare that all data supporting the findings of this study are available within the article or in references.

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G.S.M., W.J.B., and B.M.S. all contributed to the initial conceptualisation of the paper. G.S.M. led the writing of the paper with all authors contributing to the writing and revisions of drafts. G.S.M. is the corresponding author.

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ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to Geneviève S. Metson.

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