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Research article

Mapping phosphorus hotspots in Sydney's organic wastes: a spatially explicit inventory to facilitate urban phosphorus recycling

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Abstract

Phosphorus is an essential element for food production whose main global sources are becoming scarce and expensive. Furthermore, losses of phosphorus throughout the food production chain can also cause serious aquatic pollution. Recycling urban organic waste resources high in phosphorus could simultaneously address scarcity concerns for agricultural producers who rely on phosphorus fertilisers, and waste managers seeking to divert waste from landfills to decrease environmental burdens. Recycling phosphorus back to agricultural lands however requires careful logistical planning to maximize benefits and minimize costs, including processing and transportation. The first step towards such analyses is quantifying recycling potential in a spatially explicit way. Here we present such inventories and scenarios for the Greater Sydney Basin's recyclable phosphorus supply and agricultural demand. In 2011, there was 15 times more phosphorus available in organic waste than agricultural demand for phosphorus in Sydney. Hypothetically, if future city residents shifted to a plant-based diet, eliminated edible food waste, and removed animal production in the Greater Sydney Basin, available phosphorus supply would decrease to 7.25 kt of phosphorus per year, even when accounting for population growth by 2031, and demand would also decrease to 0.40 kt of phosphorus per year. Creating a circular phosphorus economy for Sydney, in all scenarios considered, would require effective recycling strategies which include transport outside of the Greater Sydney Basin. These spatially explicit scenarios can be used as a tool to facilitate stakeholders engagement to identify opportunities and barriers for appropriate organic waste recycling strategies.

Key words: circular economy, waste management, biogeochemistry, agriculture

Introduction

Cities and the circular economy

Cities have a key role to play in transitioning society towards more sustainable resource management (Childers et al. 2014; Loorbach and Shiroyama 2016; Wolfram 2016). Cities are home to over 50% of people globally and an even higher percentage in developed countries like Australia. Urban areas concentrate the demand for food and other goods, and at the same time concentrate large amounts of waste. Because of this concentration, cities are important 'linch-pins' in production–consumption–disposal chains (Rees and Wackernagel 1996). This means that resource management within a city not only has effects locally, but affects livelihoods and natural resources in the urban and rural ecosystems on which a city depends (Foley et al. 2005; Folke et al. 1997; Wackernagel et al. 2006). In addition, urban resource management affects the people and ecosystems that are 'downstream' from the city who absorb and treat their waste (Kennedy, Cuddihy, and Engel-Yan 2007).

As such, cities can play an important role in transforming society towards a more circular economy by shifting consumption patterns and managing waste products as resources to be reused (Ghisellini, Cialani, and Ulgiati 2016; Qian and Wang 2016). Although part of this important role is associated with the emergent properties of the large density of consumers making decisions, there is also power in the capacity of central organizations to make decisions about what, how, and when waste is managed. These processes are sometimes called closed-loop supply chains or reverse logistics where the collection, transport, and recirculation back up the value chain is explicitly planned, and/or from the onset, post-consumer products are designed to be returned to the producer for reuse (or a new producer for a different use, Dekker et al. 2013; Govindan, Soleimani, and Kannan 2015). This circular-economy or reverse logistics framing is a stark contrast to managing waste with an eye on exclusively minimizing negative environmental or human impacts; it emphasizes the need to manage these items or materials as resources.

That is, while diverting organic waste from landfills can have benefits such as reducing methane generation (hence greenhouse gasses), reducing land and water pollution and saving valuable land in growing cities; intentionally recovering the valuable resources in organic waste (energy, nutrients, bioactive ingredients) can also provide other key benefits. For example, diversion and subsequent recycling has the potential to reduce the consumption of virgin raw materials, increase the security of local resource supply and even reduce energy footprints through shorter supply chains, all while still meeting residents' needs of waste management. The cost and logistical implications of extracting, processing, and transporting these recycled materials can be potentially prohibitive when compared to the extraction of new resources. However, it is important to note that the price of many resources is increasing globally, and that currently the full cost of virgin raw materials is often not accounted for in the market price. This makes it difficult to compare raw and recycled resources, although price differences are often cited as a barrier to increasing recycling organic waste (e.g. on nutrient recycling, Koppelaar and Weikward 2013; Sharpley et al. 2016).

The importance of phosphorus and recycling

One unlikely critical global resource that cities can contribute to managing more sustainably is phosphorus. Phosphorus is a non-substitutable nutrient in agriculture universally, making access to sufficient phosphorus fertiliser for any country's food system a key component of food security (Childers et al. 2011; Cordell and White 2014; Elser and Bennett 2011). Geological phosphorus resources—and access to those resources—is highly uneven and inequitable, and increasingly so. That is, mineral phosphate rock used to produce fertilizers is an increasingly scare non-renewable resource of which 85% of known reserves are concentrated in just three countries—Morocco alone controlling three-quarters (Cordell and White 2011; Cooper et al. 2011).

In addition to these scarcity concerns, phosphorus losses to waterways can be seriously problematic. When lost from agricultural systems or from cities via erosion or runoff, phosphorus can fertilize cyanobacteria and algae in rivers, lakes and oceans, causing them to overgrow (Anderson, Glibert, and Burkholder 2002; Bennett, Carpenter, and Caraco 2001). These potentially toxic blooms of microorganisms can affect our capacity to use water resources for drinking water and recreation when blooms occur; even when blooms are not toxic, the decomposition of the microorganisms can cause local hypoxia affecting fisheries and local ecosystems (Dodds et al. 2009; MacDonald et al. 2016; Michalak et al. 2013).

Fortunately, there are many behavioural, political and technological solutions to facilitate more sustainable phosphorus resource management (Cordell and White 2013). Cities can play a particularly key role in one of those aspects: the recovery and reuse of phosphorus from organic wastes, including human excreta, food waste and landscaping (green) waste, back towards agricultural production (Chowdhury et al. 2014). Recycling urban phosphorus back in to agricultural production can decrease dependence on scarce mineral phosphorus fertilizers and as such phosphorus recycling can allow for a more circular urban food economy (e.g. Metson and Bennett 2015; Roy 2016). Under the right circumstances, recycling could also decrease the amount of waste ending up in downstream waterways if (1) recycling includes up-grading connections to treatment plants and the level of treatment of wastewater that would otherwise end up in waterways and (2) if the application of recycled phosphorus is accompanied with agricultural practices that increase efficiency and decrease losses to waterways.

Because costs, logistics and market acceptability are often significant barriers to increasing recycling, it is paramount that practitioners have access to information that allows them to take advantage of multiple benefits at once and minimize costs. For example, because organic waste has a high water content it is heavy, thus making transportation expensive. As such, minimizing transport distances can be important to minimizing costs. To optimize the logistics of transportation however, one must have access to spatially explicit data on the production of organic waste as well as demand. The outcome of such an analysis may include a decision to invest in higher levels of processing to decrease water content and ship recycled products further. Still, to decide what amount and type of organic waste should be further processed, and how it should be transformed, also requires waste managers and resource uses for a specific region to come together to make decisions that are compatible with each stakeholders' goals. These types of detailed analyses are required to move from large-scale theoretical analyses of potential recycling to real-world actionable change. In summary, to move forward with data-driven interventions, stakeholders require relevant information on phosphorus supply and demand to be expressed in regionally specific and spatially explicit ways.

The Australian context

Australian cities, and the Greater Sydney Basin more specifically, constitute an interesting case study to examine how geospatial phosphorus quantification can inform the development of a circular economy. Australia is an appropriate context because almost 90% of the population live in coastal cities. Further, despite the country's relatively small population by global standards, Australia is the world's fifth largest importer of phosphate, making it vulnerable to supply disruptions and price fluctuations. Sydney is the most populous cities in Australia, and new geospatial land-use data produced by the State government for the Greater Sydney Basin could be leveraged to create phosphorus maps.

National (Cordell, Jackson, and White 2013) and Sydney-scale (Tangsubkul, Moore, and Waite 2005) phosphorus budgets already exist for Australia. These budgets quantified the magnitude of phosphorus (in kt/a of P) flowing between major sectors, including mining, trade, fertilizer production, food production, consumption, waste management and losses to the environment. Local stakeholder involvement around the phosphorus sustainability issue has highlighted that resource management improvements are needed to ensure long-term food security at both the local and national scale (Cordell et al. 2014, 2017).

Existing national and regional phosphorus flow analyses aid identification of opportunities, vulnerabilities and potential intervention points to improve efficiency and increase recycling. However, much work remains to create significant real-world changes. At the national scale, the livestock sector is the largest contributor to phosphorus flows. Although Australia is a net food exporter, it is an importer of phosphorus, with over 60% of demand going to fertilize pastures to feed animals, as well as some direct import for animal feed (Cordell, Jackson, and White 2013). At a city scale, phosphorus mostly enters Sydney as food and detergents, with 45% of phosphorus inputs leaving the urban area through wastewater disposal and limited recycling such as biosolids (Tangsubkul, Moore, and Waite 2005). Based on these quantifications at national and urban scales, a wide range of potential interventions were identified. However, there is still a lack of consensus around the most feasible and desirable trajectory for phosphorus management in Australia, as well as a lack of data to make evidence-based decisions from local to national scales (Cordell et al. 2014).

One underlying implementation challenge is that phosphorus-related solutions must align with other resource management and policy priorities, including water, waste and livelihood security, to both drive change and maximize potential synergies with other interventions (Cordell et al. 2014). Although over 96 levers have been identified in the Australian food system to increase sustainable phosphorus management (Cordell et al. 2014), none of these have been implemented or taken seriously at any significant scale. Part of this lack of intervention may be related to missing economic incentives, where the market price of mineral fertilizers is still less than phosphorus derived from recycled sources (which may in turn be related to infrastructure and technological 'lock-in', making it difficult and expensive to change how waste is managed). Finding markets for recycled phosphorus can also be a challenge because of existing legal frameworks, nutrient needs on farms (ratio of nutrient needs vs nutrient content of recycled products) and concerns around health and safety (Metson et al. 2018). Although various technologies, and full cost assessments instead of market pricing, can overcome some of these barriers (Egle et al. 2016; Peters and Rowley 2009; Wang et al. 2008), the specific combination of technologies, policies and practices need to be determined within a specific region with stakeholders.

At the city scale, several options for phosphorus recycling have also been identified for the Sydney area, such as Biological Nutrient Removal from coastal wastewater treatment plants, urine diversion toilets (Tangsubkul, Moore, and Waite 2005) and more recently anaerobic digestion co-digestion with wastewater (Turner et al. 2017); however, there are significant challenges to implementing these, including knowledge gaps about how to most effectively make changes to existing food and waste systems (Cordell et al. 2017). Managing phosphorus in the Sydney Basin has been explicitly linked to water scarcity priorities (Tangsubkul, Moore, and Waite 2005), but future management must also consider emerging issues of waste management (Fam et al. 2017; Turner et al. 2017), competing land uses, soil fertility and food security (Wynne, Cordell, and Jacobs 2016). Managing some of these issues may be synergistic with sustainable phosphorus management. For example, seasonal water scarcity has (and continues to) position wastewater recycling in the region as a technical and policy option for Sydney, which could also result in increased phosphorus recycling (Tangsubkul, Moore, and Waite 2005). In addition, New South Wales (NSW) waste management goals state that by 2021 the government plans to 'increase the waste diverted from landfill from 63% (in 2010–11) to 75%' and state that 'major untapped waste sources are food and garden organics, which account for almost half of the average household waste' (NSW Environment Protection Authority 2014). The realization of such a policy would significantly increase phosphorus recycling. Further, the Australian Government is releasing a National Food Waste Strategy with a target to halve food waste by 2030 (http://www.environment.gov.au/minister/frydenberg/media-releases/mr20170411.html, accessed 31 May 2018), which, if achieved, would further drive the recycling of phosphorus from organic waste to agriculture and other end use markets.

However, there are potential barriers to increasing phosphorus recycling related to other existing city priorities. For example, the Greater Sydney Basin (Fig. 1) is planning to accommodate an additional 1.6 million residents by 2030, with the largest amount of growth planned in the Western part of the Basin, where most of the agricultural land is located (NSW Department of Planning & Environment 2014a). The land use plan that accompanies this projected growth does not explicitly protect agricultural lands, which will exacerbate the already steady decline in agricultural lands (Merson et al. 2010; Wikkinson 2011; Wynne, Cordell, and Jacobs 2016), resulting in less potential agricultural land to recycle phosphorus for local food production (in 2011 approximately 20% of Sydney's food supply came from the surrounding region, Sydney Food Futures 2016). Indeed, the Sydney Food Futures project found that 60% of food production could disappear by 2031 without any support to protect agricultural land and farming (Cordell et al. in press; Sydney Food Futures 2016; Wynne, Cordell, and Jacobs 2016). In addition, vegetable farms within the Sydney area already have high phosphorus concentrations in their soils, in part because of intensive production practices and the over application of local organic fertilisers like chicken manure, which increases the risk of phosphorus loss to waterways and causing eutrophication (Chan et al. 2007). This is in stark contrast to most Australian rural agricultural soils, which are phosphorus deficient (Commonwealth of Australia 2001). Increasing local recycling on these already high phosphorus soils could exacerbate phosphorus losses to waterways and thus considering this fact in a recycling strategy could further limit local phosphorus recycling through the local Sydney food system.

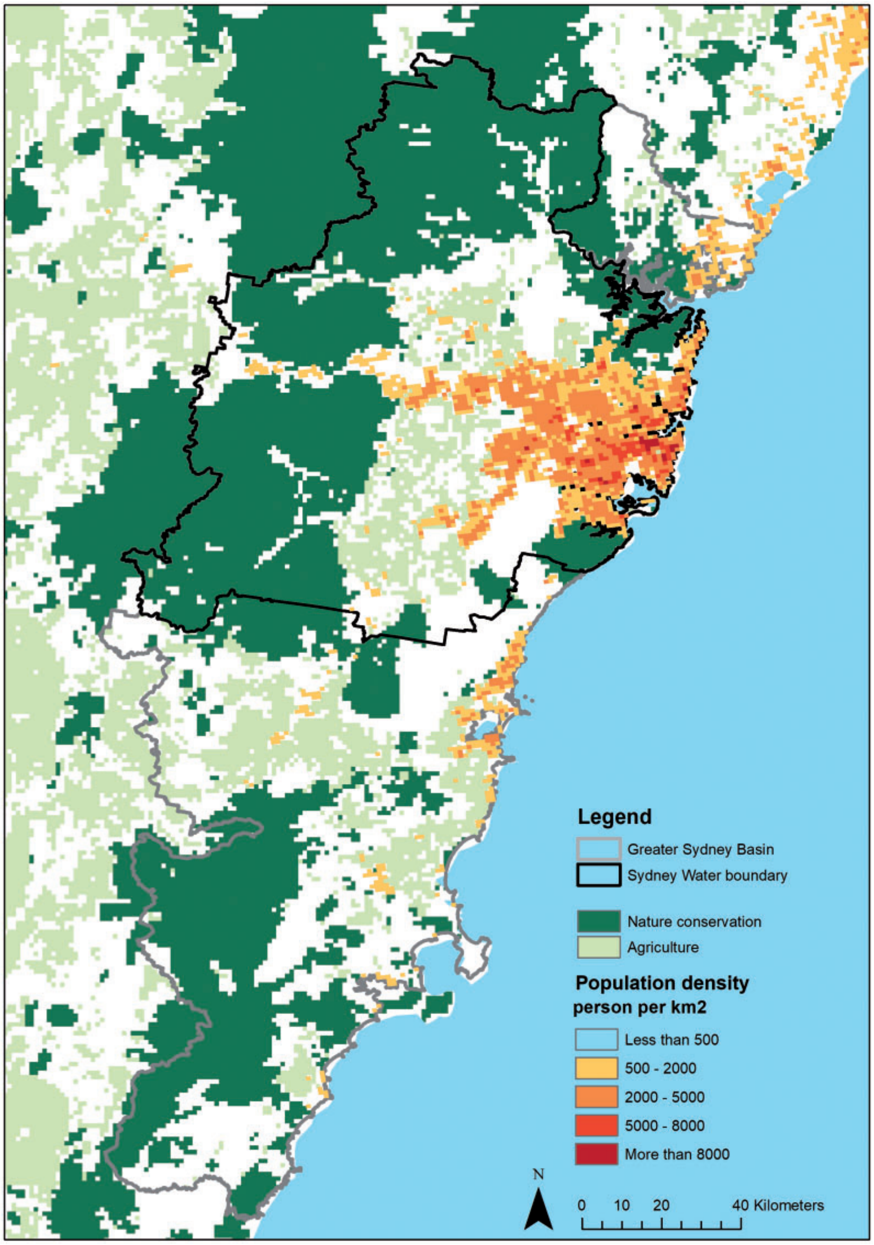

Figure 1: Delineation of the Greater Sydney Basin. Sydney is geographically bounded by ocean to the east, mountains to the west, and national park to the north and south. Black lines indicate the area serviced by Sydney Water and is used as the boundaries for the Sydney Basin in our 2011 Current system analysis. Grey lines indicate the boundaries of the agglomeration of local government areas included in our definition of the Greater Sydney Basin for future scenarios. Light green indicates agricultural land use, while dark green indicates conservation land use, mostly as parks, where agricultural or urban expansion is not possible (Department of Agriculture and Water Resources 2016). The yellow to red colouring indicates population density in 2011 (Australian Bureau of Statistics 2014)

Integral to determining how to maximize synergies and minimize trade-offs between the local priorities mentioned above and sustainable phosphorus management is a detailed understanding of the movement and magnitude of phosphorus in the Greater Sydney basin and being able to share and overlay these datasets with relevant stakeholder data and priorities. For example, a detailed spatial analysis is needed to determine where crop phosphorus demand is (crop type, soil phosphorus content) and how it may change (land use change related to city planning or climate change risks) in relation to organic waste production and processing. This allows one to see how issues related to food production, urbanization, and even environmental protection, may interact on the landscape and affect phosphorus cycling. These analyses in turn may help determine transport costs and feasibility related to alternative mixes of interventions that meet multiple goals at once.

Research objective

To increase recycling of urban wastes, and the phosphorus they contain, the availability and need for phosphorus within a regional context needs to be quantified (Chowdhury et al. 2014; van Dijk, Lesschen, and Oenema 2016). Quantifying and subsequently mapping recyclable resources is essential to determining which types of technologies, policies or behavioural changes could facilitate recycling. Similarly, it is important to examine potential end users of such recycled phosphorus to ensure that it is in a form that can be utilized and supplied in the correct amount (Melia et al. 2017; Sharpley et al. 2016).

The research presented here addresses a need for an up-to-date, regionally specific geospatial inventory and visualization of phosphorus flows in the Greater Sydney Basin. This research need was identified by stakeholders and researchers at the Australian national scale (Cordell et al. 2014). The need for spatially explicit urban phosphorus budgets generally has also been highlighted by Chowdhury et al. (2014), Metson et al. (2012) and Li and Kwan (2017). Specifically within the Sydney context, maps were identified as a valuable and necessary tool by local stakeholders at a workshop which examined urban phosphorus management to ensure urban food and water security in a cross-city context as part of the P-FUTURES project in early 2015 (Cordell et al. 2017; Iwaniec, Metson, and Cordell 2016). Some environmental management and waste management stakeholders were particularly interested in using maps as a way to combine and standardize data sources that were not being used across sectors or across locations, and eventually create estimates of costs and logistical requirements to link supply and demand. Creating spatially explicit dataset would also be a way to more easily, and visually, interact with numbers. For example, agricultural data on phosphorus and organic waste management of phosphorus are not often put together in a way that allows stakeholders to see how they are coupled (or not coupled) spatially, or how this may change in the future. In summary, mapping was identified as a first step to be able determine the economic and energy viability of different interventions, and how these interventions may take advantage of co-location of phosphorus supply and demand.

Our research aims to provide an evidence base and a tool to inform planning and implementation of locally appropriate phosphorus recycling options in Sydney. To meet this objective, we quantified the supply of organic phosphorus as a potential recyclable resource and phosphorus demand through local agriculture in the Greater Sydney Basin and then created maps of potential supply and demand in 2011 and 2031. Subsequently we hosted preliminary stakeholder workshops to explore these spatial data and identify next steps to make the maps more useful.

Methods

To quantify phosphorus resources (supply) and agricultural phosphorus needs (demand) in the Sydney region, we used a substance flow analysis framework (Baccini and Brunner 1991; Brunner and Ma 2009) applied in a spatially explicit way (similar to Metson et al. 2012) and building from Tangsubkul, Moore, and Waite (2005). We analysed the current situation (section 'Current system 2011') and two future scenarios in the following sections: 'Decentralised scenario 2031' and 'Altered consumer preferences and behaviours scenario 2031'. 2011 was chosen to indicate the current situation due to availability of datasets for this year. The year 2031 was selected for the future scenarios to link to pertinent Sydney metropolitan strategy 'A Plan for Growing Sydney' which focused on 2031 (NSW Department of Planning & Environment 2014a). We selected these two scenario options as indicative rather than predictive futures, as two options that combine waste management and consumption behaviour changes that are part of the 'toolbox' that urban stakeholders may choose from to increase sustainable phosphorus management. This analysis also built on the spatially explicit model of food production and consumption undertaken in a parallel project referred to as 'Foodsheds project' later throughput this manuscript (Sydney Food Futures 2016; Wynne, Cordell, and Jacobs 2016).

The system boundary for this study was the organic waste management and agricultural sectors of the Sydney Basin. More specifically, we consider flows of phosphorus as animal manures, wastewater and biosolids (human excreta + other industrial sources), food and green waste, and phosphorus crop demand. However, due to different administrative boundaries used by different sectors (e.g. wastewater provisioning vs organic waste collection or urban planning), we needed to choose two sets of spatial boundaries. For the current system analysis, we looked at local government areas within the Sydney Water provision area and refer to this area as the Sydney Basin (Fig. 1). The first Sydney Basin definition includes local government areas that are within a 50 km radius of downtown Sydney. To accommodate future population growth, it was logical to expand the spatial boundaries and be consistent with the 'Foodsheds project', which created spatially explicit models of future land use and population density (Sydney Food Futures 2016). We refer to this area as the Greater Sydney Basin, and include selected local government areas within a 200 km radius of downtown, which is within the range of potential truck transport of organic waste (The range of potentially feasible truck transport depends on the cost of fertilizer, the cost of petroleum, the local agricultural demand for phosphorus among other things and thus can change. We base this radius on current transport distances of biosolids from Sydney to NSW farms. For example, a farmer in Newbridge NSW which is over 200km from Sydney http://www.abc.net.au/news/2017-09-09/farmers-using-human-poo-to-improve-their-production/8887512, accessed 31 May 2018.). The change in spatial boundary between current and future scenarios has implications for the amount of potential P supplied (i.e. more people and animals), but more significantly for the potential demand of P because these outer local government areas have more agricultural lands (Fig. 1). As such, caution must be taken when comparing values in the Current system and the future scenarios.

Current system 2011

We quantified the potential demand of phosphorus from agricultural crops, and the supply for potentially recyclable phosphorus within the Sydney basin in 2011 more specifically for:

- animal manures
- wastewater and biosolids
- food and green waste

Data were sourced from State and National governments, water authorities and academic papers, preferencing spatially distributed and Sydney-specific data. Where such data were unavailable, we sought regional, national or finally global estimates of organic material and/or phosphorus concentrations. Table 1 details data sources for each phosphorus flow, major assumptions for the current system as well as the two scenarios, and Table 2 provides spatial information.

We calculated and spatially distributed crop phosphorus demand based on a high-resolution dataset of land use in the Sydney basin (1 m^2 aggregated in to polygons for each land use category, NSW Department of Planning & Environment 2013).The dataset distinguished between 26 crop categories grown in the region. Each crop category's phosphorus uptake per land area was calculated based on a weighted average of regional crop yields (Australian Bureau of Statistics 2012; McGahan and Tucker 2003) and their corresponding phosphorus content (Cordell et al. 2014; McGahan and Tucker 2003). Grazing and non-irrigated pasture

Table 1: Equations, assumptions and specification, and data sources used to quantify phosphorus flows for Sydney under the Current system 2011 and two scenarios for 2031

P flow equation (kt/a of P)	Assumptions and specifications	Data sources
Current system 2011		
Wastewater and biosolids = SUM of P in all treatment plants: (treatment plant y effluent × phosphorus concentration) + (treatment plant y biosolid production plant × phosphorus concentration) + (treatment plant recycled water x phosphorus concentration)		Sydney Water Corporation (personal communication 2015)[a]
Food and green waste = Population of Sydney × (organic waste collected and landfilled + collected and composted centrally + composted at home) (kg per capita) × phosphorus concentration of (organic waste collected and landfilled + collected and composted centrally + composted at home)	• Population is the residential population for the Greater Sydney Region area, excluding the Gosford and Wyong Local Government Areas, which matches the Sydney Water service area • Assumed that NSW per capita waste generation was representative of Sydney • Assumed that centrally recycled organic matter was 20% food and 80% green waste by weight based composition of collected recycled materials considering only green waste, food waste, and assuming that mixed food and green waste and miscellaneous municipal waste was 50% green and 50% food (Recycling Organics Unit 2011) • Assumed that organic matter going to landfill was food waste (because per capita food waste calculated based on diet was higher than estimates of organic waste sent to landfill per capita) • Used the phosphorus content of the average waste produced by the current Australian diet for food waste • Assumed organic matter composted at home was green waste	Population: (Australian Bureau of Statistics 2011) Organic waste amount: (Hyder Consulting 2012) P concentration: Green waste: (Cordell et al. 2014) Food waste based on 2011 diet composition (Australian Bureau of Statistics 2015) following: (Ridoutt et al. 2014) methods, phosphorus concentrations (FSANZ 2010)
Animal manure = SUM of animal categories: # of animals in category y × phosphorus excreted in category y (t/animal year)	• Considered dairy cows, cattle, sheep, poultry (broilers and layers) and pigs • Used a weighted average of values between chicken layers and broiler (and considered non-chicken birds to be broilers)	Number of animals: (Australian Bureau of Statistics 2012) P excreted: (Cordell et al. 2014)
Crop demand = SUM of all crop categories: # of ha in crop category y × yield of representative crops for category y (t/ha) × phosphorus concentration of category y (%)	• Weighted average of broad acre and hay crop yields for general cropping land use category • Weighted average of all fruit crop yields for general perennial horticulture land use category • Used the total number of fruit and nut trees divided by orchard area to get the # trees per ha and thus yield, as yields were expressed as weight per tree • Used the stocking density of olive trees for oleaginous crops (Olive Agencies Information Services 1997)	Area of crop categories: (NSW Department of Planning and Infrastructure and GHD Pty Ltd, 2012) Crop yields: (Australian Bureau of Statistics 2012; McGahan and Tucker 2003) P concentrations: (Cordell et al. 2014; McGahan and Tucker 2003)

(continued)

Table 1: (continued)

P flow equation (kt/a of P)	Assumptions and specifications	Data sources
	• Pasture yield and phosphorus requirements were from (McGahan and Tucker 2003) (using dryland pasture high yield values for grazing vegetation, and high yield irrigated pasture cut values for irrigated modified pastures). • Grazing and non-irrigated pasture land phosphorus requirements are expressed as net phosphorus requirements by subtracting the amount of phosphorus returned to land by cattle (99% of phosphorus excreted) and dairy (90% of phosphorus excreted) production from initial crop phosphorus requirements. • Used same yields for irrigated and non-irrigated areas except for pasture • Used vegetable yields for flower production • Assumed there is not a need to apply more than phosphorus taken up by plants considering the high phosphorus status of Sydney basin soils (Chan et al. 2007), and this is an assumption commonly used in sustainable phosphorus studies (Metson and Bennett 2015)	
Decentralised scenario 2031 (future scenario 1)		
P flow equation (kt/a of P) P in human excreta[b]= Population of Greater Sydney × (P in excreta + phosphorus in food waste + phosphorus in green waste), Where: P in excreta = SUM of food groups: reported consumption food group y × phosphorus concentration of food group y And P in food waste = SUM of food groups: reported consumption food group y × fraction of edible and inedible waste for food group y × phosphorus concentration of food group y	**Assumptions and Specifications** • Population is based on modelled outputs from the 'Foodsheds project' (see Table 2) • Assumed same sex and age breakdown in Sydney as in Australia to get an average diet • Conversions for phosphorus content assumed density of milk is 1.03 g/ml • Assume 100% of phosphorus ingested is excreted • Assumed per capita green waste created per capita is the same than in current situation (thus 80% of centrally composted waste + 100% of home composted waste) • Food waste ratios based on Australian diet include everything after farm losses and thus may be high (we assumed that on average all food waste after farm losses was recoverable in Sydney)	**References** Food consumption and waste ratios: (Australian Bureau of Statistics 2015) following (Ridoutt et al. 2014) methods Food phosphorus concentrations: (FSANZ 2010) Green waste quantity: (Hyder Consulting 2012) Green waste phosphorus concentration: (Cordell et al. 2014) Population: (NSW Department of Planning and Environment 2014b) and spatially distributed by (Sydney Food Futures 2016)
Animal Manure (see Current system)	• Population of animals is based on modelled outputs of agricultural land use from the 'Foodsheds project' (see Table 2)	Area under animal production: (Sydney Food Futures 2016)

(continued)

Table 1: (continued)

P flow equation (kt/a of P)	Assumptions and specifications	Data sources
Crop demand = SUM of all crop categories: # of ha in crop category y × yield of representative crops for category y (t/ha) × phosphorus concentration of category y (%)	• Area of agricultural crops is reduced based on modelled population increase and land use changes from the 'Foodsheds project' (see Table 2).	Crop area: (Sydney Food Futures 2016) and Department of Agriculture and Water Resources (2016) Crop yields: (Australian Bureau of Statistics 2012; McGahan and Tucker 2003) P concentrations: (Cordell et al. 2014; McGahan and Tucker 2003)
Altered consumer preferences and behaviours 2031 (Future scenario 2)		
P flow equation (kt/a of P)	**Assumptions and Specifications**	**References**
Human excreta = Population of Greater Sydney × (P in excreta + phosphorus in food waste + phosphorus in green waste), where P in excreta = same as 2031 decentralised but a diet with no animal products and P in food waste = same as 2031 decentralised but no animal products and only multiply by inedible waste fraction	• No animal products = Converted meat, dairy, eggs, and seafood categories to beans based on protein content.	P concentrations: (FSANZ 2010)
Animal manure N/A	• Assumed there was no demand for meat and thus no animal production in the Greater Sydney Basin.	
Crop phosphorus demand = SUM of all crop categories: # of ha in crop category y × yield of representative crops for category y (t/ha) × phosphorus concentration of category y (%)	• Area of agricultural crops is reduced based on modelled population increase and land use changes from the 'Foodsheds project' (see Table 2).	

[a]Data on WWTP phosphorus discharge is also available through Sydney Water and EPA monitoring reports at http://www.sydneywater.com.au/SW/water-the-environment/how-we-manage-sydney-s-water/wastewater-network/epa-reports/index.htm, accessed 31 May 2018.
[b]In the future scenarios, P in human excreta may be in the forms other than current wastewater and biosolids. For example, digestate, urine, struvite, etc.

Table 2: Spatial specifications for mapping phosphorus flows on the landscape

Current system 2011	
Flow type	**Specifications**
Animal manure	• Used same land-use category polygon layer as Crop demand, but applied manure values to animal rearing land-uses. • Total phosphorus from each type of animal was divided by the area in intensive production for said animal category and applied to land-use categories polygons with the following specifications: - Intensive animal production (dairy and sheep) we assumed that 10% of total phosphorus excreted for each category was in intensive land uses - Intensive animal production (cattle) we assumed that 1% of total phosphorus excreted was in intensive land uses - Intensive animal production (general) we assumed that 25% of the area was poultry, 25% was pig production, and rest was allocated to horses and dogs and as such applied phosphorus supply rates per area for this land-use equivalent to this weighting.
Wastewater and biosolids treated in wastewater treatment plants	• Applied an average of total phosphorus available for recycling (effluent+biosolids+recycled water) for inland and costal wastewater treatment plants. • Locations for Sydney Water plants obtained through (Geoscience Australia 2015)
Food and green waste in landfills and compost plants	• Used NSW Environmental Protection Agency Licenses for Composting and Land Application of Putrescible Waste (landfilling), then geocoded plant locations with http://www.latlong.net/, accessed 31 May 2018 • Total phosphorus processed (Table 1) was 1st applied to meet maximum licenses allowances and the divided equally between other plants
Home composting	• Per capita estimate of phosphorus processed through home composting was multiplied by $1km^2$ density map from (Australian Bureau of Statistics 2014)
Crop demand	• P crop demand applied to land-use categories polygons (NSW Department of Planning & Environment 2013). • Used ALUM2 categorization and applied the appropriate crop category phosphorus demand to the polygon area. • Resolution was $1m^2$ and projected in GDA94: MGA 56 in QGIS
Future scenarios 2031	
Animal manure	• Same as current situation but reduced agricultural area as per section 'Decentralised scenario 2031' (and population desirability and density described below)
Human phosphorus Supply	• Per capita estimate of human phosphorus supply (human excreta+food & green waste) in both scenarios were multiplied by the modelled population density maps created to spatially accommodate projected population growth developed in the 'Foodsheds' *project* (Sydney Food Futures 2016). • The estimated population in each LGA in 2031 was projected and reported in the NSW Department of Planning & Environment Plan for a growing Sydney (2014a). • The method of determining the population of a cell in an LGA is estimated by calculating the desirability of the square, the population rank of the cell, and finally the population in that cell. The variables and equations are described below.

Variable	Equation	Specifications
Desirability of a cell for new housing and infrastructure to accommodate population growth	The distance desirability is calculated directly from the distance the cell is to the CBD, specifically: $dis\tan ce\ \ desire = \exp(A.dis\tan ce\_to\_cbd\ ^2 + B.dis\tan ce\_to\_cbd + C)$ where A is 1.40×10^{-4}, B is -5.35×10^{-2} and C is 8.57. This empirical calculation was estimated by comparing the average population density to the distance to the CBD.	• Each cell lives in a 5×5 km grid locality. • Each cell in a locality has a % of services land uses, in the cell. • The serviceability of the locality is the average of the services of all cells in the locality. • The desirability of a cell is determined as the distance desirability multiplied by the serviceability of the locality the cell is in. The desirability of the cell is the multiplication of service desirability, distance desire and the populatability of the land. • The populatability of the land was a naught one dummy variable to determine if the land was populatable. For example, if the land type was a river, then the populatability would be 0.

(continued)

Table 2: (continued)

Current system 2011			
	Population weight	$Population\ \ weight = Desireability + \max\left\{Desireability - \frac{population\ \ density}{Density\ \ comparison}, 0\right\} + \frac{population\ \ density}{Density\ \ comparison}$ The density comparison is a constant, and is the line of best fit for the plot of population density versus desirability and has a value of 0.018.	• The desirability of a cell is converted to a population weight, from which the population of the cells in an LGA can be determined. • A cell that is desirable should have a high population weight. If a cell is desirable, but currently sparsely populated then the cell is likely to be a key growth area, and hence the population weight should be given an additional boost. • If cell has a high population density, then it's probably a nodal centre (such as Hornsby, Parramatta) and these nodes are assumed to be highly desirable and hence the population weight is boosted. • The population for a cell is determined directly proportioning the LGA's projected population by the population weighting.
	Population of a cell	the population in a square is: $population = \frac{population\ \ in\ \ LGA\ \ X}{\sum_{(squares\ in\ \ LGA\ \ X)} Population\ \ weight \times Population\ \ weight}$	
Crop demand	• Same as P demand by crop type as Current system but with reduced agricultural area as per the modelled population growth maps developed by the 'Foodsheds project'. • Agricultural land outside the Sydney Basin in 2011, where high resolution agricultural land use maps were available, were mapped based on the Department of Agriculture and Water Resources (2016) land use maps which use the same categorization as the NSW Department of Planning & Environment (2013), but at a resolution of 0.01 degree pixel size. Through the modelled population growth mapping however, this was resampled at a much higher resolution.		

land phosphorus requirements were expressed as net phosphorus requirements by subtracting the amount of phosphorus returned to land by beef cattle (99% of phosphorus excreted in manure) and dairy (90% of phosphorus excreted in manure) production from initial crop phosphorus requirements.

Similarly to the crop removal estimates, we quantified the amount of phosphorus available to recycle in animal manure by multiplying the number of dairy cows, cattle, sheep, poultry (broilers and layers) and pigs in the Sydney Basin (Australian Bureau of Statistics 2012) by their respective annual phosphorus excreted (Cordell et al. 2014). We then equally distributed the amount of phosphorus for each animal type on the area mapped for each type of animal rearing; excluding the manure assumed to be recycled in situ while grazing (as described in the crop demand calculation).

We mapped and quantified potentially recyclable phosphorus from biosolids and wastewater using Sydney Water data on the amount of phosphorus processed, discharged, and recycled at each wastewater treatment plant (Sydney Water 2011; Personal Communication with Sydney Water). Sydney Water managed all 25 wastewater treatments plants within the Sydney Basin. We then used the average values for coastal and inland plants in maps as the treatment and the fate of phosphorus is quite different between these two types of facilities. Each facility was geo-located using Geoscience Australia's database (Geoscience Australia 2014).

Food and green waste was quantified and mapped using a combination of site-specific, Sydney-wide and State information. We multiplied the Sydney Basin population for 2011 (Australian Bureau of Statistics 2011) by New South Wales estimates of food and green waste that was landfilled, collected and recycled centrally, or recycled at home (Hyder Consulting 2012). The amount of organic waste landfilled and centrally recycled was allocated based on putrescible waste licenses for landfilling and composting, dividing the amount left after this allocation to those facilities which did not have limits on the amount of organic waste accepted at the facility. To convert organic waste estimates to phosphorus content, we determined the proportional composition between food and green waste, using their corresponding phosphorus concentrations [green waste according to (Cordell et al. 2014) and food waste based on 2011 diet composition (Australian Bureau of Statistics 2015)] following (Ridoutt et al. 2014) methods, phosphorus concentrations (FSANZ 2010). We used NSW Environmental Protection Agency Licenses for Composting and Land Application of Putrescible Waste (landfilling), then geocoded plant locations with http://www.latlong.net/, accessed 31 May 2018 based on street addresses and verified these locations based on 'Google Maps satellite view'. The distribution of phosphorus in home composting was done based on 2011 population density (Australian Bureau of Statistics 2014).

Initial maps were created in QGIS (QGIS Development Team 2015) by overlaying the potential supply and demands of phosphorus considered for 2011. However, to make these data interactive and easily accessible to stakeholders and further create compatible spatially explicit scenarios for 2031, we created rasterized data in 100 m×100 m squares that could be projected with Google Earth. The various spatial datasets (Table 2) were rasterized by taking a gridded square mesh of the Sydney Basin, and by using the centroid of the square to determine which polygon's attributes should apply to the square. In addition, for each polygon, the attributes of the polygon are passed to the square which contains the polygons centroid. Where a square had multiple attributes assigned to it, the attributes were evenly weighted (Fig. 2). These polygons, and their associated crop type, animal type and population were used as the basis for future scenario development.

Decentralised scenario 2031

This scenario represents a future where wastes are managed at a more local or distributed scale, such as households. This could include household or neighbourhood composting of food and green waste, small-scale wastewater treatment plants or potentially urine and excreta separation and storage for later collection at a processing plant. The scenario is in fact showing the distribution of the production of organic waste and recyclable phosphorus as opposed to any specific technology adoption. Here we considered the larger area of the Greater Sydney Basin instead of the Sydney Basin boundary used in the 2011 Current system (Fig. 1). Specifically, both modelled future scenarios included Kiama, Gosford, Shellharbor, Shoalhaven, Wingecarribee and Wallongong local government areas which were not included in the Current system (These additional LGAs represent an additional 852 268 residents in 2011 compared to the Sydney Basin area.). Using 2011 as the base year for both land use and population density, the 'Foodsheds' project developed a future land use database/map that would accommodate the projected additional 1.6 million residents to the Greater Sydney Basin (Sydney Food Futures 2016).

The projected population of a local government area was estimated from State government data (NSW Department of Planning & Environment 2014a). This local government area wide population was distributed to the cells in the local government area by calculating a desirability of the cell (see Table 2). Within the 'Foodsheds' project, the desirability of a cell was determined primarily by the distance the cell is to the Central Business District (CBD), and the relative amount of services nearby the cell. In other words, a cell with a high desirability should have a higher population. Additionally, if a cell is desirable, but currently sparsely populated then the cell is likely to be a key growth area, and hence the population weight was higher. Finally, if a cell had a high population density, then it was assumed to be a nodal centre (such as Hornsby, Parramatta) and these nodes were assumed to also increase in density, hence the population at these nodes was increased as well. Through this process, some cells that were in agricultural production in 2011, and as such accounted for potentially recyclable phosphorus as animal manure and crop phosphorus demand, were converted to 'high' population density in the model. This shift altered the amount of recyclable phosphorus supply and demand expected in 2031. Crop yields and phosphorus content and animal excreta and phosphorus content were kept at 2011 levels (Table 1).

This scenario assumed that instead of centralized solid and liquid waste management, decentralised options would be favoured. As such, the 2031 population density drives the distribution of phosphorus in biosolids, wastewater, and food and green waste. We used estimates of average Australian diet composition to calculate the amount of phosphorus consumed in food per year per capita [see Metson, Cordell, and Ridoutt (2016) which is based on Ridoutt et al. (2014) and Australian Bureau of Statistics (2015) data and methods] assuming 100% of phosphorus ingested was excreted. We used the same database to obtain food group waste ratios (edible and inedible fractions) to calculate a per capita phosphorus food waste estimate. Phosphorus available for recycling in green waste (per capita) was kept at the same level as in 2011. These three per capita recyclable phosphorus sources were then multiplied by the population in each grid cell and summed with manure phosphorus estimates to get the total amount of potentially recyclable phosphorus in 2031.

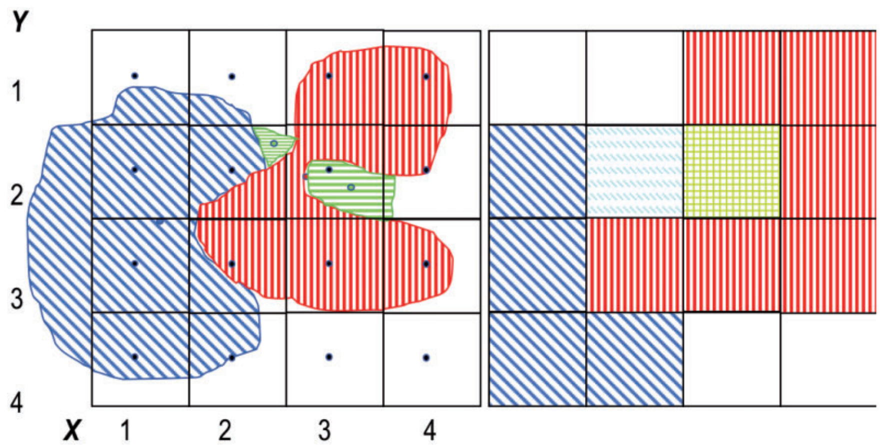

Figure 2: Diagrammatic representation of the rastering process. The cell ($x = 2$, $y = 1$) has the centroid on the edge of the blue (diagonal hashed) polygon, and is therefore assigned the blue attributes in the grid on the right of the figure. The cell (2, 3) has its centroid in the blue polygon, and there is a green (horizontal hashed) polygon whose centroid is in it, hence cell (2, 3) is an even mixture of the blue and the green (small diagonal strikes). Cell (3, 3) is two parts green to one part red (vertical hashed), resulting in a yellowy green (checkered pattern). This is because the green polygon's centroid and the red polygon's centroid are in the cell, in addition the cells centroid is in the green polygon

Altered consumer preferences and behaviours scenario 2031

In this hypothetical scenario, dietary preferences were shifted to vegetable-based and food waste was eliminated (exceeding the national government target of halving food waste by 2030). We used the same land-use and population density model and map as in the 'Decentralised scenario 2031' section but created a new future scenario where human diets and food waste behaviours were altered to decrease the demand and the supply of phosphorus within the Greater Sydney Basin in 2031 (Tables 1 and 2). Sydneysiders adopt a vegetable based diet. We converted meat, dairy, eggs, and seafood categories in the 'Decentralised scenario' diet to beans/legumes based on protein content (FSANZ 2010) (However, this results in a conservative overestimate of P consumption, as most developed economies overconsume total protein, largely due to consumption of animal protein (WRI 2016). Hence, in reality, all animal protein would not need to be replaced by legume or other plant-based protein.). This in turn affected the amount of phosphorus available in human excreta, as well as the composition of food waste. In addition, we assumed that no animals were reared in the Basin because of residents' vegetable-based diet, and as such zero phosphorus from manure was available in 2031 for recycling. This scenario also assumed that Sydneysiders stop producing edible food waste and as such further decrease the amount of phosphorus recyclable in food waste in 2031.

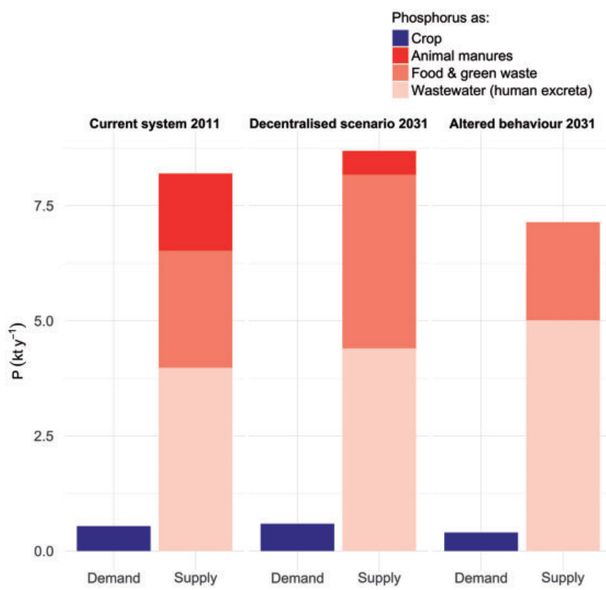

Figure 3: Potential phosphorus crop demand and recycled supply under three scenarios: 2011 based Sydney Water boundaries, and 2031 scenarios based Greater Sydney Basin boundaries

Results

The spatial analysis found that the potentially recyclable phosphorus supply in organic waste in Sydney was significantly larger than local crop phosphorus demand in 2011 as well as in both 2031 scenarios.

In 2011, the ratio of phosphorus supply to demand was fifteen. That is, the amount of potentially recyclable phosphorus in organic wastes was 15 times greater than peri-urban crop demand (8.11 kt supply vs 0.54 kt demand, Fig. 3) within the Sydney Basin. The largest potential source of phosphorus was sewage (wastewater + biosolids), representing 49% of available phosphorus sources (3.98 kt), followed by food and green waste (30%) and animal manures (20%). We estimated that 48% of this recycling potential was already being utilized, although not necessarily within the Sydney Basin, nor for agriculture. For example, 49% of phosphorus in biosolids and wastewater, mainly from inland wastewater treatment plants, was collected and returned to agricultural lands or other non-agricultural land uses such as forestry. Similarly, 44% of food and green waste produced was composted and reused, mostly in landscaping. Animal manures were also already recycled back to agricultural lands, although potentially not where there were soil phosphorus deficiencies (Chan et al. 2007). Large amounts of potentially recyclable phosphorus were geospatially concentrated at wastewater treatment plants; landfills, composting plants, and farms specialized in animal production, creating 'hotspots' of phosphorus availability in the Sydney basin (Fig. 4a and Supplementary information SI1, SI2, SI3).

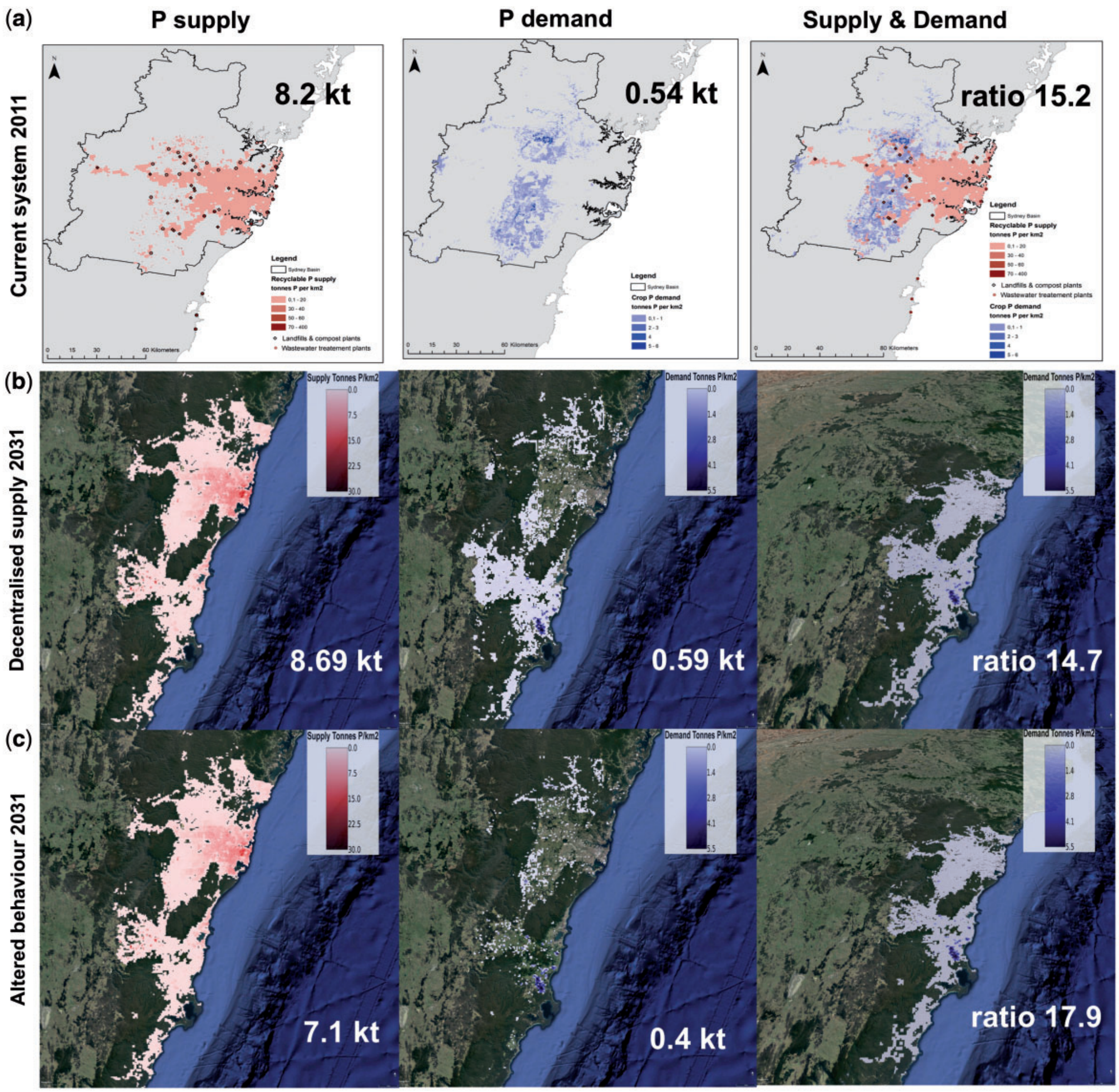

Figure 4: Spatial maps of potential phosphorus in urban organic wastes (P supply) and crop demand (P demand) under three scenarios. In all maps, red indicates the magnitude of supply (in kt/km^2) and blue indicates the magnitude of demand in the same units (total kt of supply and demand indicated by the numbers on each map). In scenario (a) Current system 2011, the Supply and & Demand map combines red and blue colouring. In future scenarios (b) and (c), which are projected using Google Earth, Supply & Demand maps also indicate demand in blue, but supply is represented by the elevation (height) of grids. The ratio number on Supply & Demand maps represents Supply/Demand in all three scenarios. *Note that the boundary of the Sydney Basin in (a) is different from the Greater Sydney Basin in (b) and (c)

The demand-side analysis indicated crop phosphorus demand in 2011 was dominated by three sectors: (1) irrigated modified pastures, (2) grazing lands (which in our study was the net demand of grazing lands after accounting for cattle manure deposited while grazing) and (3) horticultural production including vegetable and flower production. These demands however were much smaller than the potential supply of recyclable phosphorus and not as concentrated in 'hotspots' of demand on the landscape like potential recyclable sources were.

With the accommodation of an additional 1.6 million people in the Greater Sydney Basin by 2031, the 'Decentralised 2031' scenario estimated that the potentially recyclable phosphorus supply would be 14.7 times greater than crop demand (Fig. 3). The largest potential source of recycled phosphorus in this scenario would remain human excreta (4.4 kt), followed by food and green waste (3.8 kt). On the other hand, phosphorus in animal manure and crop demand would decrease by 74 and 44%, respectively, because of urban land uses such as housing and infrastructure taking over agricultural lands. The largest difference between this scenario and the 2011 reference year was the distribution of potentially recyclable phosphorus; it would be found where residents are concentrated instead of larger mega 'hotspots' related to centralized waste management (Fig. 4b and Supplementary information on data repository interactive maps). In this decentralised future scenario, there would still be more potentially recyclable phosphorus demand than supply (17.9 times), even with altered consumer preferences and behaviours by 2031 designed to decrease supply and demand of phosphorus.

In the 'Altered consumer preferences and behaviours 2031' scenario, the shift to a vegetable-based diet (and associated removal of animal production) and the elimination of edible food waste resulted in a similar map of phosphorus supply and demand as the decentralised scenario (Fig. 4b and c), but with 18% less potential supply of phosphorus to recycle. The similar distribution of supply was linked to the use of the same population density and land-use change (except animals and associated feed crops) for both scenarios for 2031. The amount of phosphorus in human waste increased to 5.0 kt, but the amount of phosphorus in food and green waste reduced to 2.13 kt while the amount in animal manure was reduced to 0. These changes in Sydneysider's diet and waste management practices in the third scenario would have implications for agriculture and food production further away. Specifically, this scenario resulted in a 12.5% decrease in supply of locally available recyclable phosphorus, but more importantly decreased the demand for phosphorus to produce food for Sydney by 72% (Metson, Cordell, and Ridoutt 2016).

Discussion

The Sydney case analysed here is indicative for other growing global cities: the potential to recycle phosphorus in urban wastes is significant and typically under-utilized. Further, most of the recyclable phosphorus would need to travel beyond the greater metropolitan region to be utilized sustainability. Finally, changing urban residents' diet and waste management practices would dramatically reduce a city's dependence on mined P which is used in the global food supply chain it currently depends on (Metson, Cordell, and Ridoutt 2016).

Consistent with Tangsubkul, Moore, and Waite (2005)'s 2000 analysis of phosphorus in Sydney, we found that less than half of the phosphorus available was recycled in 2011. We also found that the phosphorus that was recycled often left the region. For example, 26% of phosphorus entering wastewater treatment plants was recycled, but the majority of that phosphorus was transported in bulk biosolids to rural farms outside the Basin in the form of a low cost, or even free, soil amendment. Most cities recycle far less than 50% of phosphorus in waste products (Chowdhury et al. 2014). However, the use of new sanitation and waste management systems that increase nutrient recovery could theoretically fullfill local peri-urban agricultural phosphorus requirements (e.g. Wielemaker, Weijma, and Zeeman 2018), in addition to replacing fertilizers used further away from the city centre (Zhu et al. 2017). Recycling urban phosphorus sources, even if they must travel further, can become more cost effective and attractive as the price of phosphorus fertilizer increases (and/or fluctuations become more unpredictable; e.g. Vollaro, Galioto, and Viaggi 2017). However, efficiently concentrating the phosphorus and other valuable components will decrease transport distances and energy cost associated with such logistics.

Recycling strategies will need to span the urban-rural gradient in order to reconnect urban post-consumer waste back to food producers via nutrient recycling, creating a more circular economy at local, regional, and global scales (Monaco et al. 2017; Seto et al. 2012).

Spatially explicit information to facilitate a systems perspective and stakeholder dialogue

Spatially explicit scenarios of phosphorous supply and demand provide an important tool to support decision-makers. Moving from a quantitative substance flow analysis (such as classic MFA work), often portrayed as a box and arrow flow diagram, to a spatially explicit inventory of resource availability and demand can increase the usefulness of quantitative knowledge for a diversity of stakeholders including waste managers, environmental regulators, farmers, etc. (Spatially explicit inventories are only one of many ways to visualize metabolism studies: http://metabolismofcities.org/datavisualization/examples, accessed 31 May 2018.). Through workshops with diverse stakeholders, where we presented the maps, we were able define potential uses for the spatially explicit datasets, and thus a clearer roadmap to the next steps needed to make full use of these spatially explicit data (Table 3).

First, maps allow for spatial variability in phosphorus demand and supply to become apparent, which is not the case with simple quantitative material flow analyses. Having a reliable spatial understanding of supply and demand is key for effective reverse logistics, as economies of scale and transport distances can be a large factor influencing recycling logistics, costs and hence viability of the whole system (Linderholm, Tillman, and Mattsson 2012; Sharpley et al. 2016). Secondly, maps make it easier for diverse groups to see how they, and their priorities, fit within the system and visualize what changes could look like, creating planning capacity (as shown by Hillier 2017).

In Sydney, we used our current and future scenario maps to engage a diversity of stakeholders, including farmers, waste managers, agrochemical retailer and agronomists (THE CHANGING PHOSPHORUS LANDSCAPE: Risks & opportunities for agriculture and waste management in the Greater Sydney Basin http://www.p-futurescities.net/the-changing-phosphorus-landscape-risks-opportunities-for-agriculture-and-waste-management-in-the-greater-sydney-basin/, accessed 31 May 2018.). Each stakeholder group was able to identify aspects of the phosphorus mapping that were relevant to their individual needs (Table 3). For example, combining spatially explicit hydrological models with these phosphorus data could help create scenarios for pollution risks.

The largest gains for many of the stakeholders were most likely about bringing diverse stakeholders together. The stakeholder groups that were involved potentially benefited from a better understanding of their linkages to other sectors that they do not engage with on a regular basis. For example, our preliminary results in workshops using these maps indicated potential mismatches between current organic waste suppliers and farmer and their agronomic needs, when looking from a single stakeholder perspective. For example, The NSW Environmental Protection Authority (EPA) aims to increase municipal organic waste diversion from landfills by increasing recycling to 70% by 2022 (NSW Environment Protection Authority 2014). The maps of recyclable phosphorus supply created in this research, which explicitly include municipal food and green waste, can help identify 'low hanging fruit' to increase organics recycling and meet the EPA's goal. These maps can also bridge siloed thinking that may exist between stakeholders. The EPA for example considers recycling from a waste management perspective, that is, prioritizing the collection and diversion of organic waste from landfill. However, potential end-users of recycled phosphorus

Table 3: Potential users of the Sydney spatially explicit phosphorus inventory

Stakeholder group	Potential use of spatially explicit inventory of phosphorus and organic waste
Environmental regulatory agencies	• Identify potential pollution risk areas • Identify potential 'low hanging fruit' to inform policy prioritisation in terms of quantity of phosphorus or proximity to reuse areas • Prioritise appropriate organic waste flows for recycling within the Sydney Basin versus exporting elsewhere within the State. For example, based on ease of processing and concentrating the phosphorus, the value of the material, etc.
Existing waste/resource managers	• Identify current and future opportunities for collection of and markets for recycled product in the context of potential logistical limitations and opportunities that might arise • Better identify future infrastructure (and policy) opportunities to tap into the full recycling potential associated with increasing population
Local councils (responsible for municipal waste collection)	• Better identify future infrastructure and policies that allow them to tap into the full recycling potential associated with population increases
New entrepreneurs in the waste & resources sector	• Identify new reverse logistics business opportunities for a circular economy including the collection, processing, transport, and novel markets (i.e. new demand that has not been developed or identified)
Urban planners	• Inform new land-use planning policies that take into account urban agriculture, organics reverse logistics needs and opportunities and the multiple uses of each land-use type (e.g. residential land-use is not just housing, it also affects demand for food and supply of organic waste including potential phosphorus)
Wastewater utilities	• Facilitate internal planning for strategic transition from 'wastewater managers' to 'resource providers' • Identify internal opportunities for reuse and potential partnerships with other local stakeholders • Identify opportunities for cost-effective new infrastructure options to accommodate population growth (considering both decentralised and centralized options)
Fertilizer companies, nutrient service providers & agronomists	• Identify future opportunities and markets of local soil amendments and fertilizers and how they can advise farmers in how to use them appropriately to maximize productivity
Farmers	• Identify current and potential sources of phosphorus close to their farms that they may use (or potentially large distances to phosphorus source)
Research community	• Data source for future costing and logistics studies to optimize phosphorus recycling and organic waste scenario options

(such as farmers) may have other perceptions, preferences and concerns that will need to inform how phosphorus is recovered and processed into end-user products. Such end-user concerns may include: consistent quality standards, reliability of supply, availability of machinery to spread the organic material, cost, odour and demonstrated effectiveness (Dominish, Cordell, and Jacobs 2017).

The workshop identified additional considerations that need to be included in order to bridge the potential supply of recycled phosphorus to local agricultural demand within the Basin. More specifically, although we know that many Sydney Basin soils are already high in phosphorus (Chan et al. 2007), there remains a lack of clarity around specific soil and farm nutrient needs. Soil testing is not a regulatory requirement in most parts of Australia, unlike in many parts of the USA and EU where soil testing is required to determine fertilizer application levels to meet environmental regulations (e.g. Metson, Aggarwal, and Childers 2012; Metson et al. 2018). Uncertainty around soil nutrient needs in turn has important implications for sustainable phosphorus recycling. Without soil nutrient information to determine appropriate phosphorus application quantities, fertilizer practices are likely to remain the same, even if they are not in line with plant and soil needs. In Sydney, this involves over-application of affordable sources of fertilizer, including poultry manure, saturating the market and limiting entry for other new recycled organic soil amendments and fertilisers. Without clarity about farm market needs, increasing recycling can be hindered by the availability of large amounts of affordable organic soil amendments on the market. During the stakeholder workshop, using our maps, it was possible to identify fruitful lines of inquiry to facilitate increased sustainable and productive recycling. The maps helped uncover how diverse stakeholders' existing challenges and priorities were linked systematically and spatially. Workshop participants co-produced a preliminary list of compost qualities, such as the need for standardized and known levels of nutrients and contaminants, that would be useful to farmers in order to be able and willing to pay more (and responsibly use) urban recycled nutrients [This was further assessed through a subsequent project (Dominish, Cordell, and Jacobs 2017).]. In summary, the maps not only provide quantitative information, they can facilitate stakeholder identification of differing priorities and facilitate discussion and knowledge sharing to form a more systematic picture of the organics reverse logistics value chain.

Model and data limitations

It is important to contextualize these Sydney Basin spatially explicit datasets within a multi-scalar approach to sustainable phosphorus management. This work represents an important step in bridging the divide between different stakeholders' perspectives and realities (e.g. urban waste managers and farmer perspectives) but more locally specific data are still needed to make viable decisions (Sharpley et al. 2016). Although we used the most high-resolution data available, our current analyses do not fully account for spatial heterogeneity that could be important for optimizing efficiency and recycling. For example, the incorporation of smaller-scale urban agriculture land uses and nutrient practices (e.g. Metson and Bennett 2015), neighbourhood differences in organic waste production and recycling (e.g. Fissore et al. 2011), and farm specific soil phosphorus levels and fertilization practices could improve accuracy of recyclable phosphorus supply and demand within the region.

Similarly, understanding how current fertilizer, wastewater and organic waste are transported through the city could further elucidate opportunities and barriers to increasing recycling. Information beyond the spatial extent of the Sydney basin will also be important. For example, as the potentially recyclable supply of phosphorus exceeds demand by local farms, we require a better understanding of farmer needs beyond the Basin to fully take advantage of Sydney's recycling potential. In addition to thinking about what Sydney's organic waste can offer other locations, it is important to consider how Sydney may be vulnerable because of events outside the region. For example, the 'Altered consumer preferences and behaviours 2031' scenario may not seem adaptable/desirable when looked at exclusively from a local lens. In this scenario, a vegetable-based diet increases the amount of phosphorus in human excreta required to be treated and recycled in sewage while also potentially decreasing the need for phosphorus from local farmland if areas which currently produce animal products were not converted to crop production. Considering peri-urban farms offer many cultural and ecosystem services to Sydneysiders, such as urban amenity of green spaces, urban cooling, wildlife corridors and increasing the resilience of the city to extreme events in other major Australian food bowls, preservation of these lands should be a priority (Brinkley 2012; Merson et al. 2010; Wynne, Cordell, and Jacobs 2016). From a more global perspective, however, changes in diet require less phosphorus through the food chain, which could make Sydney less vulnerable to changes in fertilizer prices globally (Cordell, Turner, and Chong 2015; Metson, Bennett, and Elser 2012), even if recycling did not increase (Metson, Cordell and Ridoutt 2016).

In addition to a need to look at multiple spatial scales, further analyses on multiple time scales, as well as parsing out phosphorus source quality would be useful. We considered an annual time step, but the production and processing of organic waste happens daily and can vary by season [e.g. increased food waste in the summer as people eat more fresh fruits and vegetables (Gallo 1980) and change from residential to commercial neighbourhoods when people eat more at restaurants (Adhikari et al. 2008)]. Farm phosphorus requirements also vary with planting and growing seasons, as well as potential soil build up from previous management that must be considered to maximize usefulness and minimize losses to waterways (Sharpley et al. 2013). We considered total phosphorus in our analyses, but it is important to incorporate information on the different forms of phosphorus and chemical bonds of potentially recyclable phosphorus sources because their bioavailability and pollutant concentrations may be different, affecting their suitability for different agricultural practices (Egle, Rechberger, and Zessner 2015; Oliveira et al. 2016). In summary, considering multiple spatial and temporal scales is ultimately necessary to develop sustainable phosphorus management strategies, and the spatially explicit inventory presented here is a step toward such strategies.

Next steps

Moving forward, the inventories and interactive maps developed could be used as the basis to further engage stakeholders in the development of local and regional organic waste and phosphorus recycling strategies to meet both agricultural and urban waste management goals. Our maps can be used by stakeholders to facilitate discussions around optimization criteria to recycle phosphorus and to pin-point where new research is needed to uncover the logistical needs for recycling options (e.g. Zhu 2014). This may be particularly important for planning and minimizing transport distances and costs, as well as technology selection to facilitate near-reuse and further transport that matches farmer needs and be competitive with mineral phosphorus fertilizer characteristics (including price, form, safety, etc., Egle et al. 2016).

Options will need to consider the trade-offs of centralized and decentralised systems, and need to take into account changing land-uses and population distributions, as well as cultural acceptability by the public, farmers and food retailers (Daigger 2009; Dominish, Cordell, and Jacobs 2017; Metson et al. 2015). Because these maps can help diverse stakeholders visualize how they connect in a reverse logistics circular economy, these maps could also enable better market assessment. Such a process may also include the development of entirely new markets that allow for a better match between phosphorus supply and phosphorus demand. For example, the benefits of organic waste recycling are not just in terms of nutrients. There may be arrangements where co-benefits, such as avoided pollution, and co-beneficiaries could share the cost of recycling to maximize multiple benefits at once. In fact, these co-benefits have been responsible for past (at times unintentional) recycling of phosphorus from cities (Metson, Aggarwal, and Childers 2012; Metson et al. 2018).

In summary, we found that maps were an effective tool to break down some of the communication barriers inherit with complex urban socio-ecological systems faced with a challenging but important sustainability issue: phosphorus sustainability. Spatially explicit inventories will thus be part of our work moving forward in transdisciplinary sustainability projects (e.g. Cordell et al. 2017; Iwaniec, Metson, and Cordell 2016).

Conclusion

As phosphorus is an essential fertilizer and potential aquatic pollutant, more sustainable management of phosphorus-containing waste streams is necessary to ensure food security and water quality at national, regional, and even city scales. Cities, including Sydney, have a large recycling potential which if optimized could decrease dependence on geopolitically-scarce mined phosphorus resources while also decreasing the risk of phosphorus losses to sensitive waterways. In addition, phosphorus sustainability must be integrated in the multiple other sustainability priorities cities face including water scarcity, waste management, land use change, population growth, affordability and equity.

We found that Sydney produces significantly more recyclable phosphorus than there is demand from local agriculture. As such, linking with farms and other end-use markets outside of the Sydney Basin will be necessary to take advantage of this recycling potential and foster a more circular phosphorus economy. Taking a spatially explicit approach translated complex data into a useful format for diverse stakeholders to gain a better understanding of barriers and enablers to recycling. Developing these spatially explicit datasets is the first step in being able to run optimization scenarios to explore transport logistics and cost under different scenarios; all of which can be constrained based on stakeholder goals and interests. The research presented here falls in line with some of the top research questions identified in the field of coupled human and natural systems: food production and land use change (Kramer et al. 2017), and does so in a way that allows scientists to move beyond nutrient accounting and into real world transitions by acknowledging the importance of governance and the role of multiple stakeholder perspectives (Muñoz-Erickson et al. 2016).

Supplementary data

Supplementary data are available at *JUECOL* online.

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Conflict of interest statement. None declared.

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