Plant-based diets add to the wastewater phosphorus burden

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Keywords: phosphorus, diet, wastewater treatment works, sustainability

Abstract

Global food production and current reliance on meat-based diets requires a large share of natural resource use and causes widespread environmental pollution including phosphorus (P). Transitions to less animal-intensive diets address a suite of sustainability goals, but their impact on society’s wastewater P burden is unclear. Using the UK as our example, we explored historical diet changes between 1942 and 2016, and how shifting towards plant-based diets might impact the P burden entering wastewater treatment works (WWTW), and subsequent effluent P discharge to receiving water bodies. Average daily per capita P intake declined from its peak in 1963 (1599 mg P pp
−1 d
−1) to 1354 mg P pp
−1 d
−1 in 2016. Since 1942, the contribution of processed foods to total P consumption has increased from 21% to 52% in 2016, but consumption of total animal products has not changed significantly. Scenario analysis indicated that if individuals adopted a vegan diet or a low-meat (‘EAT- Lancet’) diet by 2050, the P burden entering WWTW increased by 17% and 35%, respectively relative to baseline conditions in 2050. A much lower P burden increase (6%) was obtained with a flexitarian diet. An increasing burden of P to WWTW threatens greater non-compliance with regulatory targets for P discharge to water, but also presents an opportunity to the wastewater industry to recycle P in the food chain, and reduce reliance on finite phosphate rock resources. Sustainable diets that reduce food system P demand pre-consumption could also provide a source of renewable fertilizers through enhanced P recovery post-consumption and should be further explored.

1. Introduction

Agriculture is one of the largest drivers of resource use and environmental degradation across the planet; for instance, it accounts for a third of the global greenhouse gas (GHG) emissions causing anthropogenic climate change (Le Quéré et al 2015). Food consumption patterns are linked to agricultural outputs and therefore indirectly affect the environment, whilst dietary choice has a direct effect on human health. Consequently, there is mounting pressure to alter dietary habits to help reduce GHG emissions, excessive eutrophication and ecosystem decline, while also tackling the proliferation of global undernourishment, micro-nutrition deficiency and obesity (FAO 2017, Baker 2019). Transition to more healthy plant-based diets for adults has been widely advocated to help improve future environmental and human health across the globe (Tilman et al 2002, Springmann et al 2016, 2018, Poore and Nemecek 2018, Willett et al 2019). The recent EAT-Lancet supported diet (which is low-meat) is a high-profile example of the type of dietary shift suggested to keep the planet within its safe operating spaces by 2050, whilst meeting global nutritional needs (Willett et al 2019). However, food production and dietary patterns have a complex impact upon critical natural resources across multiple scales, including phosphorus, which must be carefully considered.

Phosphorus (P), is an essential nutrient and finite resource that underpins global agricultural production but inefficiencies in its use within the food chain, and largely one-way open life cycle (from phosphate rock mines, to fertilizers, to fields, to foods, to sewers and eventually to waterways) is causing costly, long-term degradation of our rivers and seas (Childers et al...
Livestock density is a major driver of this P inefficiency and pollution due to the extra land and fertiliser P required to produce animal feed and the difficulties of recycling livestock excreta evenly back to croplands (Leip et al 2015, Withers et al 2020). Increasing global demand for animal food products has increased the demand for mined P by 28% since 1961, and 90% of the environmental P footprint for an individual UK resident is due to animal product consumption (Metson et al 2012). As such, transitioning towards a plant-based diet seems beneficial for P sustainability by reducing global P fertilizer demand and lowering eutrophication rates by reducing individual P footprints (Macdonald et al 2012, Metson et al 2012, Thaler et al 2015).

There is already evidence suggesting meat-eaters in Westernised Nations are considering plant-based foods. Sales of these foods increased 20% in the US worth ~$3.3 billion in 2018 (Plant Based Foods Association 2018). In the UK, sales of plant-based products increased 14.5% in 2017 (Ethical Consumer 2018) and, in 2018, the UK food industry launched more vegan products than any other nation (Mintel 2019). The recent Ipsos Mori survey indicates that vegetarian and vegan diets increased 360% between 2006 and 2016 in the UK, comprising now 3.25% of the population (Ipsos MORI 2016), whilst flexitarian diets are estimated to now comprise ~21% of the population (Waitrose & Partners 2018). Such dietary transitions may continue to rise in countries such as the UK as consumers increasingly make dietary changes due to concerns over human health, the environment or animal welfare (Ethical Consumer 2018); noting of course that many emerging economies are still increasing per-capita consumption of animal products.

If food consumption patterns are to change towards plant-based diets, it is necessary to not only look at how they may affect upstream resource use and downstream eutrophication impacts, but also to better understand how these diet changes might affect waste management capacity and the potential to sustainably recycle P back into the food chain. Taking an historical perspective is one way to better understand how diets have shifted, and may continue to shift, and better evaluate the potential impact of a change in consumption of any one food type. In the case of P, there is some evidence that while plant-based products have significantly lower environmental P footprints in terms of the fertilizer they require for production, they do result in more human P excretion (Metson et al 2016) because they contain twice as much P per gram of protein than animal-based products (Jönsson et al 2004, Kalantar-Zadeh et al 2010). Consequently, a transition to plant-based diets may increase the P burden entering wastewater treatment works (WWTW) and the investment required to remove P in the influent and warrants further significant investigation (Metson et al 2016).

2. Methods

2.1. Trends in dietary P consumption in the UK (1942-2016)

We estimated average dietary P consumption (mg P day⁻¹) per person between 1942 and 2016 based on the per capita consumption of different food types and their P content. This was necessary because the UK National Diet and Nutrition Survey does not report daily average P consumption. Food consumption data were taken from the UK National Food Survey (Defra 2011) for the period 1942–1973, and from the UK Family Food Survey for the period 1974–2016 (including takeaway data) (Defra 2018). These surveys allowed quantification of both fresh and unprocessed food and processed food categories. Fresh and unprocessed foods included unprocessed cereals, fresh fish, meat, dairy, eggs, vegetables and fruit. Processed foods included processed cereals, fish, meat, dairy, vegetables, fruit, sugars, other foods (canned soup, beverages and condiments), fats, and takeaway foods (e.g. on-the-go sandwiches, meals eaten out or bought at food outlets). Food quantities for each category were then multiplied by the P content of the edible portion of each food (therefore only accounting for actual consumed food) as detailed in McCance and Widdowson’s The Composition of Foods Integrated dataset (Finglas et al 2015, Public Health England 2015). Possible changes in the P content of foods over time were assessed by using...
successive versions of the McCance and Widdowson databases (table S1), although it is recognised that this is only a crude indicator of changing mineral composition (White and Broadley 2005). Where the edible portion was not listed for a particular food, we used the next editions edible portion data (table S1). Takeaway P content was compiled separately (table S2). The derived edible P content (mg P 100 g\(^{-1}\)) was multiplied by the amount consumed per day (mg) to give average P consumption (mg P day\(^{-1}\)) per person for each food type. Trends in consumption were smoothed by loess regression analysis. Further information on the food survey calculations, and the limitations of using food survey and food compositional data are discussed in Supplementary Information.

2.2. Trends in dietary P burden to WWTW in the UK (1942-2016)

To calculate the dietary P burden entering WWTW (kt P year\(^{-1}\)), the per capita dietary P consumption was multiplied by UK population (Office for National Statistics 2015) for the respective year and converted to kilo tonnes (kt). As humans only retain ~6% of consumed P during childhood years (2–17 years old), after which healthy adults remain in P homeostasis and only absorb enough P to replace excreted ‘old’ P they have consumed (Jönsson et al 2004), we assumed that estimates of total per capita P consumption provide a suitable metric of per capita P excreted and entering WWTW. Our estimates were validated by comparison to the average per capita P excreted (0.524 kg person\(^{-1}\) year\(^{-1}\)) as reported by Naden et al (2016), and the median value of other published estimates (0.376–0.596 kg person\(^{-1}\) year\(^{-1}\)) reviewed by those authors. We did not include the negligible amounts of P in wastewater arising from in-house wastage of liquid foods.

2.3. Dietary change scenario analysis (2016-2050)

Potential changes to the wastewater P burden as a result of future dietary change up to 2050 were assessed in four different scenarios which included a baseline scenario. These scenarios required us to: (1) estimate the per capita P consumption associated with five diets that would span a range of P sustainability outcomes; (2) determine the proportions (%) of the future UK population that follow these different diet options; and (3) multiply these per capita rates by the total projected UK population over time.

A meat-based diet was based on the average daily P consumed in 2016 as calculated from the family food survey. An average vegan dietary P consumption (mg P day\(^{-1}\)) was calculated by substituting the animal derived protein (meat, fish, dairy and eggs) consumed in the average meat-based diet with the protein equivalent supplied by beans and legumes as in Metson et al (2012), Metson et al (2016), and as recommended as an option by the National Health Service in the UK (NHS 2018). For a vegetarian diet, only the protein from meat and fish products was replaced with beans and legumes. A flexitarian diet assumed meat and fish was consumed 3 d a week, which equates to a 47% reduction in meat and fish consumption compared to average 2016 consumption habits in the UK. We therefore replaced the protein from this 47% reduction in meat and fish with beans and legumes. For a recommended healthy diet, we used the EAT-Lancet diet with median macronutrient intake (g day\(^{-1}\)) values, in which animal products contribute 25% (334 g) to the total nutrient intake per day or 12% of total calories (median 2425 kcal day\(^{-1}\)), (table S3). Calculated daily dietary P consumption for the five different diets along with their calorie and protein content is reported in Table S4.

Descriptions of the four scenarios incorporating changing proportions of these diets over time are summarised in table 1. The baseline scenario largely represents the average meat-based diet in the UK. Although scenario 1 assumes a predominantly vegan population and such a transition is not without complexity, there is evidence that a strong decline in meat consumption is possible and even likely in the UK (see Supplementary Information). Scenario 2 assumes flexitarian diets will become more popular, whilst scenario 3 represents a recommended healthy diet that helps to limit environmental impacts (Willett et al 2019); it contains a diversity of plant foods, less animal foods, less saturated fat and less processed food, refined grains and sugars. Per capita annual P consumption rates (mg P per person year\(^{-1}\)) for each scenario were combined with the projected population rise in the UK for the years 2016 to 2050 (Office for National Statistics 2017) to estimate the total dietary P load entering WWTW (kt P year\(^{-1}\)) to 2050. Scenario analyses were not intended to be predictions but to illustrate examples of the potential impact of dietary shifts on the P burden.

2.4. Discharges of wastewater effluent P to water (2016-2050)

Discharges of wastewater effluent P to water from both WWTW and septic tanks for each dietary scenario were calculated to provide an estimate of the increased amount of P that will require removal. The ca. 9288 WWTW in the UK were classified into six size bands according to their total treatment capacity (based on person equivalents (p.e.)), and their actual p.e. load requiring treatment (table S5 and S6). Total dietary P loads for each scenario (p.e. load x daily P consumption per person) were combined with estimated industry P contributions to calculate the total P load (kt yr\(^{-1}\)) entering each size band of WWTW (and septic tanks). Current rates of P removal at different sized WWTW based on median P retention factors for primary, secondary, tertiary and
advanced P removal treatment technologies calculated by Naden et al (2016) were then applied to these loads to estimate the effluent discharge of P to water (kt yr$^{-1}$) for each scenario to 2050. Further details of WWTW size bands, p.e. capacities and loads, their P removal efficiencies, and calculation of industry contributions and septic tank discharges are given in Supplementary Information and table S5 and S6.

2.5. Dietary effect on P compliance targets at a sub-set of WWTWs (2016-2050)

To assess the impacts of the scenario changes in diet on river P compliance targets set by water regulators under the EU Urban Wastewater Treatment Directive (UWWTD), we investigated a subset (448) of the larger WWTWs (>2000 p.e.) that have data on the p.e. load entering the works, and the P inflow and outflow concentrations for 2018. These 448 works are records of P inflow/outflow concentration data (249 works in bands 3–6) according to their p.e. capacity, and calculated the percent of P removal for individual works we calculated the outflow concentration. Average removal percent for the band 5% and 6 works combined was 83%, minimum and maximum removal was 38.5% and 98.7% respectively. Average removal percent for the band 4 and 3 works combined was 82%, minimum and maximum removal was 14 and 98% respectively. When the average outflow concentration exceeded either 1 mg P l$^{-1}$ (bands 5 and 6) or 2 mg P l$^{-1}$ (bands 3 and 4), we deemed the works to be non-compliant.

A t-test (assuming unequal variances) was performed to determine whether compliance of works was significantly different under the different dietary scenarios in the year 2050.

3. Results

3.1. Historic dietary P consumption in the UK (1942-2016)

Since 1942, the total dietary wastewater P burden has increased to over 30 kt P yr$^{-1}$ due to the increase in the UK’s population (figure 1(a)), which rose from 47.9 million to 65.6 million in 2016. Despite some annual fluctuations, there has been a general small decline in average P consumption per person in recent years (figure 1(b)), which mirrors a general decline in total food consumed (figure S1 (available at stacks.iop.org/ERL/15/094018/mmedia)). The consumption of food increased as the nation recovered from war-time shortages and rationing, until ~1950 s (~1600 g food person$^{-1}$ d$^{-1}$), when food survey data suggest a continual decline in consumption until the present day (2016, ~1400 g food person$^{-1}$ d$^{-1}$). Total consumption of vegetables, dairy, and cereal based foods showed particular declines, whilst consumption of fruit showed a marked increase (figure S1(b)). Phosphorus consumption (figure 1(b), figure S1(b)) peaked in 1963 at 1599 mg P day$^{-1}$ (per person) after which it decreased to 1354 mg P day$^{-1}$ in 2016; average P consumption over the period was 1486 ± 70 mg P day$^{-1}$. This equates to

| Table 1. Dietary change scenario descriptions. |
|---------------------------------------------|
| **Description**                             |
| **Baseline scenario**                       |
| The baseline scenario assumes no change in dietary consumption patterns of the population: 3.25% vegetarians (2.09%) and vegans (1.16%), and 96.75% eating the current meat-based diet. |
| **Scenario 1: transitioning to vegan diets** |
| Scenario 1 assumes a predominantly vegan population in 2050. Initially the current ratio of vegan and vegetarians (1.62) does not change and the percent of the population that is vegan or vegetarian increases 13% annually. The remaining percent of the population consumes a meat-based diet until 2045 whereby none of the population consume meat. At 2045 vegetarian diets decline at a rate of 13% a year, whilst veganism continues to increase to constitute 70% of the population in 2050. |
| **Scenario 2: transitioning to flexitarian diets** |
| Scenario 2 assumes that 21% of the population is currently flexitarian (Waitrose & Partners 2018), the current percent of vegan (1.16%) and vegetarians (2.09%) does not change, and meat-based diets decline as flexitarian diets increase by 13% annually until 2030 whereby meat-based diets remain stable at 10% of the population. |
| **Scenario 3: transitioning to the EAT-Lancet diet** |
| Scenario 3 assumes meat-eaters transition to the EAT-Lancet diet by 2050 (3% increase a year in percent of population which has EAT-Lancet diet) and the current population percent of vegetarians (2.09%) and vegans (2.26%) remains the same. |
Table 2. Average concentration of phosphorus (mg P l$^{-1}$) in influent and effluent from Urban Waste Water Treatment Works in the UK with P compliances (works must achieve effluent outflow P concentrations of 1 or 2 mg P l$^{-1}$ for bands 5 and 6 or 4 and 3, respectively) in 2018, and the estimated percent removal of P from these works.

| Band | BOD5 kg day$^{-1}$ | p.e. capacity$^a$ | Target mg P l$^{-1}$ | No. works | Total p.e. Capacity | Total inflow l | Influent P | Effluent P |
|------|-------------------|-------------------|----------------------|-----------|---------------------|----------------|------------|------------|
|      |                   |                   |                      |           |                     |                | Average    | No. records | Average    | No. records | st.dev P l$^{-1}$ |
|      |                   |                   |                      |           |                     |                | mg P l$^{-1}$ |           | mg P l$^{-1}$ |           |                      |
|      |                   |                   |                      |           |                     |                | No. records |           | No. records |           | st.dev P l$^{-1}$ |
|      |                   |                   |                      |           |                     |                | Average P removal % |           |                      |
| 6    | >1500             | >25 000           | 1                    | 200       | 18 074 264          | 3 614 852 800 | 128       | 6.91       | 1.89       | 194        | 0.99                      | 0.50       | 85.7       |  
| 5    | >600, ≤1500       | 10 000–25 000     | 1                    | 181       | 2 136 935           | 427 387 093  | 121       | 7.15       | 2.39       | 171        | 1.06                      | 0.50       | 85.1       |  
| 4    | >120, ≤600        | 2000–10 000       | 2                    | 62        | 303 308            | 60 661 600   | 46        | 7.17       | 2.84       | 62         | 1.17                      | 1.64       | 83.7       |  
| 3    | >30, ≤120         | 500–2000          | 2                    | 3         | 5871               | 1 174 200    | 1         | 7.78       | 0.00       | 3          | 0.38                      | 0.06       | 95.1       |  

$^a$p.e., person equivalent expresses the average weekly load from industrial and domestic activities as equivalent to the load generated by a given number of people, where it is assumed that 1 person makes a contribution of 60 g BOD$_5$ day$^{-1}$ of organic biodegradable load and 200 l day$^{-1}$ of wastewater flow (Butler Manufacturing Services 2013).
Figure 1. (A) Total phosphorus (P) load (kt P yr\(^{-1}\)) entering wastewater treatment works from diets in the UK (1942-2016). Green is our current study estimated load; blue is the estimated load in Naden et al (2016), both with loess regression lines. (B) Average UK P consumption per person per day (mg P pp\(^{-1}\) d\(^{-1}\)) using the UK National Food Survey (triangles), Family Food Survey (circles), and the seven editions of the McCance and Widdowson food composition database, blue line is loess regression. (C) Average UK P consumption per person per day (mg P pp\(^{-1}\) d\(^{-1}\)) for total fresh foods (fresh vegetables, fruit, fish, milk, meat, and unprocessed cereals) and total processed foods (processed vegetables, fruit, fish, milk, meat, and cereals, sugars, other products and takeaways), with loess regression lines.

0.494 kg P person\(^{-1}\) year\(^{-1}\), which is comparable to the range of per capita P excretion (0.376–0.596 kg person\(^{-1}\) year\(^{-1}\)) published in Naden et al (2016) calculated from multiple studies, giving us confidence that the data sources used here were reliable. Until the late 1970s, dietary P intakes from fresh foods increased but then subsequently declined due to an increase in the consumption of processed foods.
Figure 2. Average phosphorus (P) load to wastewater treatment works (kt P yr$^{-1}$) from dietary scenarios 1, 2, 3 and baseline. Black line is baseline scenario (no change in the current proportion of meat-eaters, vegetarians and vegans), blue line is the total P load for each scenario. Purple, grey, red, green and yellow dashed lines are the load contributions from the EAT-Lancet, flexitarian, meat-based, vegan and vegetarians’ diets, respectively, used in the scenarios.

In 2016, 699 mg P day$^{-1}$ came from processed foods (~52% of the total daily intake per person), compared to 292 mg P day$^{-1}$ in 1942 (~21% of the total daily intake) (figure 1(c)). In 1942, cereal products comprised 41% of the UK dietary P consumption (figure S1(b)), but this declined to 23% by 2016, with an increasing proportion coming from processed cereal products (figure S2).

3.2. Contribution of animal products to the UK diet (1942-2016)

Total animal product consumption per person increased from 3252 g per week in 1942 to a peak of 4618 g per week in the late 1960s and then declined to 3008 g per week by 2016 (figure S1(a), figure S3). The overall contribution from meat, fish, dairy and eggs to dietary P intake has therefore not changed significantly between 1942 and 2016, comprising 48% of the total dietary P intake in 1942 and 50% in 2016, peaking at 59% in 1973 (figure S3).

Meat consumption per person increased 19% from 1942 (746 g per week) to 2016 (891 g per week), but peaked in 1980 (1160 g per week, a 56% increase since 1942). A gradual decline in total meat consumption (figure S1(a)) between 2000 and 2016 equated to an approximate 12% reduction, and a 15% reduction to dietary P intake from meat products (figure S1(b)). However, meat products are still the third largest contributor to total dietary P intake after dairy and cereals, and total P consumed in meat products increased 28% from 1942 to 2016, most likely due to the increased consumption of processed meats (figure S2).

Consumption of dairy products overtook cereals as the most significant contributor of the total dietary P intake in 1956 and peaked in 1963 (figure S1(b)) before declining to 29% of dietary P intake by 2016. High P containing products such as cheese, yoghurt, and other milk products (e.g. dairy desserts and milk drinks) have increased in their proportion of the average diet, whilst liquid whole milk consumption declined 88% between 1974 and 2016 to be largely replaced by skimmed milk products. However, this switch to skimmed milk did not result in a total increase in the dietary P intake from dairy but mediated the effect of such a large decline in liquid milk consumption, keeping dairy as the most significant contributor to both the total dietary P intake (figure S1(b)) and the total dietary P intake from animal products (figure S3).
3.3. Effect of dietary change on the P burden to WWTW (2016-2050)
Assuming no change in the dietary habits of the UK population, the P burden to WWTW is estimated to increase 23.8% over the period 2016 to 2050, from 32.5 to 40.2 kt P yr$^{-1}$, and is accounted for by predicted population increase (figure 2, black line). Adopting a predominantly vegan diet (scenario 1) would increase the P burden by 45% from 32.5 kt P yr$^{-1}$ in 2016 to 47.2 kt P yr$^{-1}$ in 2050. This is a 17% increase in P burden compared to the baseline scenario in 2050. A predominantly flexitarian diet would increase the dietary P burden in 2050 to 42.6 kt P yr$^{-1}$ from 33 kt P yr$^{-1}$, a 6% increase compared to the baseline scenario in 2050. The EAT-Lancet diet would increase the dietary P burden by 67% from 32.5 kt P yr$^{-1}$ in 2016 to 54.4 kt P yr$^{-1}$ in 2050, an increase of 35% compared to the baseline scenario (figure 3). This scenario results in the largest change in dietary P burden.

3.4. Effect of dietary change on discharges of wastewater effluent P to water (2016-2050)
This analysis assumes WWTWs will always have the capacity to deal with the increase in population to 2050, but assumes that the percent of works with either primary, secondary, tertiary or P-removal technologies does not change. If diets do not change (the baseline diet), effluent discharges to water are estimated to increase by 24% from 10.7 to 13.3 kt P yr$^{-1}$ in 2050. Our analyses suggest that if the population were to become predominantly vegan (scenario 1), or eat the EAT-Lancet diet (scenario 3) by 2050, discharges of P to water from septic tanks and WWTW could increase by 44 and 64% compared to 2016 levels to 15.4 and 17.5 kt P yr$^{-1}$, respectively (figure 3), assuming current rates of P removal. A 31% increase in discharges to 14 kt P yr$^{-1}$ is likely by 2050 for flexitarian diets (which reach a peak in 2029), which is 5% more than the baseline scenario in 2050. However, discharges of P in 2050 will be 17% more than the baseline scenario if 70% of the population is vegan and 30% is vegetarian (scenario 1), and 32% more if 96% of the population is eating the EAT-Lancet diet (scenario 3).

3.5. Effect of dietary change on P compliance targets at a sub-set of WWTWs (2016-2050)
The scenario analysis assumes the p.e. received at the individual works does not change and that no further investment by the water industry is made to increase the efficiency of existing P-removal technologies (average 83%–95% removal efficiency, table 2) at the sub-set of WWTWs we analysed. By 2050, 65, 61, 73 and 57% of the selected WWTWs will be non-compliant under scenario 1 (vegan), 2 (flexitarian), 3 (EAT-Lancet) and the baseline respectively. The baseline and flexitarian diet demonstrate relative effluent P concentration stability (and are not significantly different, $t = 0.99$, $p > 0.05$, figure 4) compared to the vegan and EAT-Lancet diets, as the change in dietary effect is less than the change in population effect; meaning that P load to the WWTW does not increase more than the litres of water produced by the population served, hence concentration remains stable. Both the vegan ($t = 2.74$, $p < 0.05$) and EAT-Lancet diets ($t = 5.13$, $p < 0.05$) significantly increase the number of non-compliant works in the year 2050 compared to the baseline scenario.

4. Discussion
Historically, the largest change we identified in the per capita dietary P intake across the UK was a shift in diet composition, in particular a shift from fresh to processed foods, which increased from 21% to ~52% of the diet by 2016 (figure 1(c)). This distinctive change is a common trend in westernised nations.
today (Cooke 2017) and a threat to public health, as globally poor diet is considered to be a greater risk to mortality and morbidity than alcohol, drug use, tobacco and unsafe sex combined (Willett et al 2019). Increased consumption of processed foods would be expected to increase the dietary P intake, because of the inclusion of food additives containing P which has increased dramatically in the 20th century (Molins 1991, Gutiérrez 2013). The potential for such foods to be under accounted for in the food surveys may account for the slight decline in dietary P consumption since the 1970s, and more accurate accounting of processed foods would likely suggest that average dietary P consumption in the UK has remained relatively stable since 1942 at around 1500 g P day$^{-1}$ (figure 1(b)). Very similar average daily P intakes have been reported in the USA (National Academy of Sciences, 1997).

This level of per capita P intake for the average UK diet, or indeed any of the diets used in our scenario analysis, are not above the European Food Safety Agency identified Acceptable Daily Intake (ADI) of P at 2800 mg P day$^{-1}$ (EFSA 2019). However, such high levels of P intake are excessive, nutritionally redundant and consequently yield greater amounts of excreted P which requires costly treatment, disposal or recycling (Withers et al 2018, British Nutrition Foundation 2019). Reducing per capita consumption of processed foods would help to reduce daily P intake and improve population health and wellbeing (Willett et al 2019), but requires sufficient access to healthy, nutritious foods. Ironically, a transition to more environmentally sustainable diets by substituting beans and legumes for meat and dairy would increase daily P intakes by some considerable margin (e.g. over 20% for a vegan diet, Table S4). The EAT-Lancet diet gave the largest increase in per capita P intake due to the inclusion of whole grains and nuts. Whilst the calorie contents of our five diets are well aligned to current dietary reference values (2000–2500 kcals, Public Health England 2018), the protein contents of all the diets were well above recommended reference values (45–56 g day$^{-1}$, British Nutrition Foundation 2019). Further exploration of dietary composition is needed to identify healthy diets that are not only more environmentally sustainable but also do not result in unduly high P burdens entering WWTW.

![Figure 4. Concentration of phosphorus (P) (mg P L$^{-1}$) exiting UK band 5 and 6 works (total 249 works) which have a 1 mg P L$^{-1}$ discharge consent (listed by the Environment Agency in 2018 and under the Urban Wastewater Treatment Directive) under 1, 2, 3 and baseline scenarios. Outliers above the 99th percentile have been removed, middle box line is the median, the upper and lower hinges are the first and third quartiles (0.25 and 0.75), the whiskers extend to the highest or lowest values within 1.5*interquartile range of the respective hinge.](image-url)
Our results show that although population growth, and not changes in an individual’s total food P consumption, have driven historical increases in UK wastewater P burdens, the proposed changes towards more environmentally sustainable plant-based diets in the future could cause substantial increases in this dietary P burden (figure 2). For the predominantly vegan or EAT-Lancet diet, the P burden would increase by 17 and 35% to 47.2 kt P yr\(^{-1}\) and 54.4 kt P yr\(^{-1}\), respectively in 2050 compared to the baseline scenario. Metson et al. (2016) found that the average person in an Australian city changing to a predominantly plant based diet would increase the wastewater P burden from diets by around 8% (per capita). Previous studies have indicated that vegetarians have lower P wastewater burdens (Cordell et al. 1993), but these assumed that diets are often augmented by high intakes of carbohydrates rather than by intake of high-protein beans and pulses (Draper et al. 1993). Perhaps surprisingly, we did not identify any significant increase in the proportional P burden related to the consumption of animal products since 1942: animal product consumption increased between 1942 and the late 1960s but decreased after 2000, a trend also observed in Western Europe (de Gavelle et al. 2019). Yet animal products still contribute 50% of the wastewater P burden in the UK.

The increased discharges of P from WWTWs due to the changes in diet presented here (figures 3 and 4) pose two major challenges to the wastewater industry. Firstly, the removal of an increased P load to WWTWs to meet increasingly stringent compliance targets for discharge P concentrations would require significant investment in new works, and the introduction of new technologies to improve P removal efficiencies (currently 83%–95%). As an example, previous estimates have suggested that for a works of >1 million p.e. (only 7 works in the UK listed under the UWWTD) to achieve the 1 mg P l\(^{-1}\) compliance target, chemical precipitation would involve costs of ~£2 m capital expenditure and ~£0.2 m a year of operational expenditures, whilst ecological removal methods would cost twice as much (Cooper 2014). The second major challenge is the recycling of much larger volumes of biosolids to agricultural land after advanced treatment. Biosolid recycling back to the food chain is already constrained in a number of regions by concerns over their longer-term impacts on human health and the environment (Clarke and Smith 2011, Colllivignarelli et al. 2019). Although, nearly 80% of total biosolid production is recycled to agricultural land in the UK (ABS 2018), there is a limited landbank available and further biosolids loading to soils will exacerbate regional soil P accumulation and could increase the risk of diffuse losses of P to water in some areas, especially under a changing climate (Ockenden et al. 2017, Forber et al. 2018).

Yet, this poses an interesting policy opportunity for ‘knowing where the P is’ in what can currently be deemed a chaotic and wasteful food system (Withers et al. 2020). If as other studies suggest, environmental P footprints can be reduced by 20%–72% by transitioning to more plant-based diets (Thaler et al. 2015, Metson et al. 2016), then ‘pre-consumption P’ which is notoriously difficult to recover and reuse is minimised whilst ‘post-consumption P’ increases. This ‘post-consumption P’ could be argued as more recoverable as we know the location (wastewater works) and the technology required to recover it. Indeed, UK wastewater companies are expected to play a greater role in environmental protection whilst limiting any additional costs to consumers in order to maintain their licenses to operate (Ofwat 2019). If the potential recoverability of wastewater P is enhanced to produce more concentrated fertilizer products that can be transported longer distances than biosolids, then this may enable more P circularity in our food systems and reduce society’s reliance on imported, finite mineral P (Tonini et al. 2019, Withers 2019). For example, Tonini et al. (2019) concluded that the health and environmental co-benefits of using recovered fertilizer-grade P from wastewater were greater than those of using biosolids (e.g. biosolids), especially in highly populated regions.

5. Conclusions

Individual dietary P consumption in the UK declined slightly between 1942 and 2016, but the P load to WWTW still increased due to an increase in population. Contributions from animal-based foods to the total per capita dietary P intake did not significantly increase over this time period, but the contribution of processed foods increased dramatically, comprising ~52% of the diet in the UK in 2016. Although reducing animal products in diets is an effective way for UK consumers to reduce their P and other environmental footprints (e.g. Leach et al. 2016, González-García et al. 2018, Vanham et al. 2018), these footprints are not the only metric that must be taken into account when planning for a more sustainable food system. Our analysis demonstrates that widespread adoption of plant-based or ‘healthier’ diets (such as veganism and the EAT-Lancet diet), will greatly increase daily P intake and therefore impose higher dietary P burdens on WWTW, which in turn would increase point-source P discharges to water if not recovered. However, our findings do not diminish the overarching global environmental value of reducing meat production and intake since post-consumption P-recovery is much more feasible than the recovery of much more highly dispersed P pre-consumption. Indeed, in terms of water quality impairment, there are wider and more difficult non-point P source contributions to control from agriculture, and in areas of intensive livestock farming in particular, related to surplus P accumulation and recycling manures in catchments (Withers et al. 2014, Leip et al. 2015,
Shore et al 2016). Instead, we attempt to highlight the increasingly important role of the wastewater industries in the drive towards P sustainability through the provision of renewable fertilizers as part of a circular nutrient economy. Wastewater treatment works with P removal, and the efficiency of P removal technologies, will clearly need to increase to meet increasingly stringent regulatory compliance targets for P to combat the costly eutrophication of inland and coastal waters. Reducing excess food intake and wastage and consuming fresh food instead of processed food would help to minimise both the pre-consumption demand for P and the post-consumption P burden on the wastewater industry.

Acknowledgments

This paper was produced as part of the RePhoKUs project (The role of phosphorus in the sustainability and resilience of the UK food system) funded by BBSRC, ESRC, NERC, and the Scottish Government under the UK Global Food Security research programme (Grant Nos. BB/R005842/1). We would like to acknowledge the use of data relating to WWTW provided by the Environment Agency and in particular the contributions from Sally Richardson, Linda Pope and Paul Simmonds. Thanks are also due to Miller Alonso Camargo-Valero, Leeds University and two anonymous referees who provided useful comments on the manuscript.

Data availability statement

Any data that support the findings of this study are included within the article.

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