**QUEEN'S
UNIVERSITY
BELFAST**

Transforming phosphorus use on the island of Ireland: A model for a sustainable system

Macintosh, K. A., Chin, J., Jacobs, B., Cordell, D., McDowell, R. W., Butler, P., Haygarth, P. M., Williams, P., Quinn, J. P., O'Flaherty, V., & McGrath, J. W. (2019). Transforming phosphorus use on the island of Ireland: A model for a sustainable system. *Science of the Total Environment*, 656, 852-861. [656].
<https://doi.org/10.1016/j.scitotenv.2018.11.389>

Published in:
Science of the Total Environment

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

Copyright 2018 Elsevier Ltd.

This manuscript is distributed under a Creative Commons Attribution-NonCommercial-NoDerivs License

(<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Transforming phosphorus use on the island of Ireland: a model for a sustainable system

Katrina A Macintosh^{1,*}, Jason Chin¹, Brent Jacobs², Dana Cordell², Richard W McDowell^{3,4},
Paul Butler⁵, Philip M Haygarth⁶, Paul Williams¹, John P Quinn¹, Vincent O’Flaherty⁷ and
John W McGrath¹

¹ School of Biological Sciences and the Institute for Global Food Security, The Queen’s
University of Belfast, United Kingdom

² Institute for Sustainable Futures, University of Technology Sydney, Australia

³ AgResearch, Lincoln Science Centre, Christchurch, New Zealand

⁴ Soil and Physical Sciences, Faculty of Agriculture and Life Sciences, Lincoln University,
Lincoln, New Zealand

⁵ Manufacturing, Engineering and Energy Commercialisation, Enterprise Ireland, Ireland

⁶ Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom

⁷ Microbial Ecology Laboratory, Microbiology, School of Natural Sciences and Ryan
Institute, National University of Ireland Galway, Ireland

*Corresponding author.

E-mail address: k.macintosh@qub.ac.uk

20 **Graphical abstract**

21

Abstract

Phosphorus is an essential part of the world food web and a non-substitutable nutrient in all biological systems. Losses of phosphorus occur along the food-supply chain and cause environmental degradation and eutrophication. A key global challenge is to meet rising worldwide food demand while protecting water and environmental quality, and seeking to manage uncertainty around potential future phosphorus price or supply shocks. This paper presents a stakeholder-generated conceptual model of potential transformative change for implementing phosphorus sustainability on the island of Ireland via an ‘All-Island Phosphorus Sustainability’ workshop. Key transition pathways identified by stakeholders included: incentivising phosphorus recovery, developing collaborative networks to facilitate change, developing markets and value chains for recovered products; implementing data-informed practices on-farm to prevent losses and increase efficiencies, and harmonisation of technologies with end-user needs. A comparable model was previously produced for the North American region. We describe consensus and differences around key priorities between the two regions’ conceptual models, and assess how the model produced for the island of Ireland can effect system-wide change and policy moving forward. Many of the transitional pathways and future aspirations presented in both models resonate globally and are highly pertinent to other jurisdictions.

Keywords

Phosphorus sustainability; Transformative change; Island of Ireland; North America; Stakeholder engagement; Policy design

1. Introduction

1.1 Importance of phosphorus

Phosphorus is an essential part of the global food web and a non-substitutable nutrient in all biological systems (Tilman et al., 2002; Villalba et al., 2008; Sharpley et al., 2018). In many terrestrial and aquatic ecosystems phosphorus is a growth-limiting nutrient and anthropogenic inputs have led to accelerated environmental degradation (Elser and Bennett, 2011).

Eutrophication of the freshwater environment poses the most widespread single threat to good water quality globally (Withers et al., 2014). Paradoxically, despite the loss of large quantities of phosphorus to the environment – some 80% of mined phosphate is lost or wasted in the phosphorus value chain (Cordell et al., 2009) – finite reserves of high-quality phosphate rock are in decline and those remaining are of lower phosphorus concentration, and more expensive and energy-intensive to mine and process (Reijnders, 2014).

The potential for phosphorus scarcity and price volatility, which is a threat to food production and food security, is exacerbated by the geographically concentrated nature of global phosphorus reserves. Over 78% of global phosphate rock production is confined to Morocco, the US, China and Russia; in contrast, phosphorus production in Europe is minimal (van Kauwenbergh, 2010; U.S. Geological Survey, 2018). The European Community, which has for many years viewed itself as a food secure region, now recognises its vulnerability to phosphorus scarcity, as major global phosphorus reserves fall outside the collective borders of the country member states (Schröder et al., 2010). In 2008 perturbations in the global economy caused an 800% increase in the price of phosphate rock, and national shortages of fertiliser in some nations (Cordell and White, 2014; Cordell et al., 2015). Despite this, countries that import phosphate rock, such as the Republic of Ireland and the United Kingdom (UK), have been slow to adopt phosphorus recovery and recycling initiatives.

69

70 1.2 *Phosphorus sustainability on the island of Ireland*

71 Northern Ireland, which is part of the UK, and the Republic of Ireland are two distinct
72 political regions located on the island of Ireland. While these are separate legal jurisdictions,
73 both are currently legislated as part of the European Union (EU), pending the UK's planned
74 departure from the EU in 2019. European Directives, such as the Water Framework
75 Directive, the Urban Waste Water Treatment Directive and Nitrates Directive (which
76 indirectly controls phosphorus), regulate to improve water quality by addressing
77 eutrophication (McDowell et al., 2016). Phosphorus is managed through judicious use,
78 conservation and loss mitigation at source (e.g., on-farm) or via removal (e.g., wastewater
79 treatment works and industry) to protect water bodies, yet little recovery currently takes place
80 (Macintosh et al., in press). As such, the phosphorus, which is either lost to the environment
81 or landfilled, is simply replaced with newly mined virgin material. The EU Circular
82 Economy Package (European Commission, 2014; Stahel, 2016) highlights the need to bring
83 about a transition away from current linear use practices towards the recovery of critical raw
84 substances, such as phosphorus.

85

86 The agri-food sector is integral to the economy on the island of Ireland, and national
87 strategies such as 'Food Harvest 2020' and 'Food Wise 2025' (in the Republic of Ireland),
88 and 'Going for Growth' (in Northern Ireland), have been implemented to encourage growth
89 in this sector (Food Harvest 2020, 2011; Going for Growth, 2013). Achievement of the
90 ambitious growth targets embodied in these policies is intrinsically linked to the importation
91 of phosphorus-rich fertiliser products and the sustainable management of waste residues (e.g.,
92 manures; farm run-off; dairy processing and slaughter house wastes) to protect the
93 environment and ensure regulatory compliance. The phosphorus-rich wastes generated by

agriculture, industry and domestic effluents offer a compelling sustainability opportunity: up to 30% of EU demand for phosphorus could be met theoretically by its recovery from domestic waste streams alone (Gilbert, 2009; van Dijk et al., 2016). Despite this potential, sewage sludge in Northern Ireland is processed by mono-incineration with no phosphorus recovery from the ash. In the Republic of Ireland 98% of biosolids are currently disposed of to land (Irish Water, 2016). Irish Water (the primary water utility company in the Republic of Ireland) anticipates that wastewater sludge volumes will increase in excess of 80% by 2040 due to improvements in infrastructure: this has raised concerns regarding land availability to which this waste can be disposed (Irish Water, 2016).

1.3 A model for transformative change

In order to collectively design a planned and coordinated transition to a sustainable phosphorus future for the island of Ireland, a transformative change model approach was applied. This specific national model was first applied in the context of phosphorus sustainability in the North America by Jacobs et al. (2017). The model (**Fig. 1**), based on theories of transition management (e.g. Kemp and Rotmans, 2005) and economies of increasing returns (Levin et al., 2007), was used to identify what an ‘ideal future would look like to stakeholders in terms of phosphorus sustainability’ (‘Transformed System’); to establish how stakeholders viewed the existing status of phosphorus sustainability (‘Business-as-Usual’); and, to determine how they felt the current phosphorus situation could most effectively be transitioned into the idealised future that they had identified (‘Transition Pathways’). Additionally, the process required stakeholders to describe which issues they felt were impeding the adoption of this idealised future (‘Barriers’), and which factors could facilitate transition into the idealised paradigm (‘Enablers’). Finally, stakeholders identified

drivers that were stimulating society to shift to a sustainable phosphorus future ('Drivers of Change').

Phosphorus sustainability is a complex, social-ecological issue and to address it requires action at a range of spatial, temporal, jurisdictional, institutional and managerial scales and levels (Cash et al., 2006). Transformation of society's phosphorus use and management will require collaboration by a diversity of actors. As Pohl (2008) suggested, transdisciplinary approaches that initiate co-production of knowledge are appropriate to develop policy outcomes to such issues because they facilitate joint ownership, responsibility and commitment to solutions of both researchers and practitioners (Polk, 2015). Despite the problems of attempting to capture multiple framings and integrating the diversity of knowledge inherent when experts, bureaucrats and stakeholders are brought together (e.g. Edelenbos et al., 2011), knowledge co-production is seen as a useful method to facilitate change (e.g. McNei et al., 2016; Dinesh et al., 2018; van der Molen, 2018). Coupling broad stakeholder (bureaucrats and industry representatives) engagement on phosphorus to a meeting of technical experts, such as a scientific conference, through a participatory workshop process (e.g. Jacobs et al., 2017) presents a unique opportunity for knowledge co-production that has the potential to allow emergence of a focused future vision and is efficient in use of stakeholders time.

In this paper we:

- 1) Apply the transformative change process, adapted from the model developed by Jacobs et al. (2016; 2017), to capture stakeholder perspectives on phosphorus sustainability on the island of Ireland

- 2) Synthesise stakeholder knowledge to generate a conceptual transformative change model for phosphorus sustainability on the island of Ireland
- 3) Contrast the model generated in this study with a directly comparable model produced for the North American region

This study is the second time globally that the participatory transformative change model process has been comprehensively used to generate a model for phosphorus sustainability at a regional level. The implementation of such aspirational, co-produced, conceptual model provides an opportunity to engage stakeholders across diverse sectors and develop policy to implement regional management towards phosphorus sustainability. Comparison of the island of Ireland and North America models serves to highlight the global nature of the challenge of phosphorus sustainability through examination of similarities and key differences across stakeholders at differing geographical scales and regulatory environments. While stakeholder workshops assessing phosphorus vulnerability, adaptive capacity and transition pathways at the national level (e.g. Cordell et al., 2014) and city-scale (Cordell et al., 2016; Iwaniec et al., 2016) have also been undertaken in recent years, these are not directly comparable with the island of Ireland and North American models due to methodological differences. However, our study does augment the existing body of literature pertaining to stakeholder participatory approach based studies conducted on the island of Ireland, for example the development of agri-environmental mitigation strategies for the management of phosphorus to protect water quality (e.g. Schulte et al., 2009; ACP, 2017; Micha et al., 2018).

2. Methodological approach

In two projects funded by the Environmental Protection Agency of Ireland, and Science Foundation Ireland and the Department for the Economy (in Northern Ireland) researchers at Queen's University Belfast and the National University of Ireland Galway were jointly funded to identify the current and future pressures, policies and solutions that underpin phosphorus sustainability on the island of Ireland (McGrath and O'Flaherty, 2014; 2015). As part of this, the partners collaborated with researchers at the Institute for Sustainable Futures, University of Technology Sydney to elicit and synthesise views from stakeholders across the island of Ireland on the status of phosphorus sustainability in the region, and which actions – if any – they felt were necessary to protect economic output and food security in light of potential phosphorus supply issues. This information, gathered during an 'All-Island Phosphorus Sustainability' workshop, was processed and synthesised to generate a model of the pathways necessary to achieve phosphorus sustainability on the island of Ireland, which could be compared to that produced by Jacobs et al. (2017) from meetings of similar purpose with stakeholders in North America.

A total of 76 stakeholders participated in an 'All-Island Phosphorus Sustainability' workshop held in conjunction with the Microbiology Society UK Conference June 2017, in Belfast, Northern Ireland. The transformative change process, adapted from the model developed by Jacobs et al. (2016; 2017), was used to capture participant perspectives on phosphorus sustainability from the island of Ireland, in the context of agriculture, industry, wastewater and food security. This workshop afforded a unique opportunity to collect information from stakeholders across a wide range of sectors, spanning the agri-food industry, wastewater treatment sector, government institutions, regulators, technology providers and academia (**Table 1**).

A panel of invited keynote speakers and presenters (**Table S1**) stimulated stakeholder discussion in relation to perspectives on regulatory phosphorus management, phosphorus recovery, reuse and recycling, and future directions for phosphorus sustainability on the island of Ireland. Stakeholder viewpoints were captured during breakout group discussions using table facilitators and note-takers. **Table S2** shows the constituent elements of the transformational change model and questions considered by workshop participants.

The stakeholder information collected during the workshop was processed using the methodology of Jacobs et al. (2017). In short, stakeholder responses captured during the workshop were collated and manually processed to remove duplication and grouped into the transformational change model sub-categories of:

- business-as-usual: the existing status of phosphorus sustainability
- drivers of change: stimulating society to shift
- transformed system: what an ideal future would look like transition pathways: how to achieve a transformed system
- barriers: the issues impeding adoption enablers: the factors facilitating transition

Participant responses within each of the above model sub-categories were then further coded into the following common themes, which arose from the data processing:

- biophysical
- governance
- economics
- technology
- social
- knowledge and/or research
- whole system (spanning two or more categories)

- unclassified (those which do not fall under any of the above categories)

The analysis process summarised and incorporated multiple delegate responses into concise statements or ‘tag-lines’. In developing tag-lines, particular attention was paid to ensuring common themes that emerged from multiple, independently-facilitated stakeholder groups were represented in the model, a process conceptually similar to thematic saturation applied in other types of qualitative inquiry (O’Reilly and Parker, 2013). These tag-lines were then used to generate the conceptual model of transformational change and sought to reflect stakeholder viewpoints according to sub-category and theme.

Comparable with the ‘All-Ireland Phosphorus Sustainability’ workshop, the North American stakeholder event also consisted of invited talks, panel session presentations with audience questions and answers, as well as time allocated for facilitated group discussion and data capture via table facilitators. However the North American model was produced using stakeholder viewpoints gathered over a period of two days: during the inaugural meeting of the Sustainable Phosphorus Alliance board meeting (25 participants), and, the ‘Future of Phosphorus’ stakeholder event (68 participants), both held in Washington D.C. in 2015. Stakeholder perspectives on the future of phosphorus sustainability were captured from across a broad range of sectors spanning government, industry, agriculture, not-for-profit organisations, fertiliser companies and universities in the US (Jacobs et al., 2017).

3. Findings

The conceptual model of transformative change for phosphorus sustainability on the island of Ireland that emanated from the stakeholder data collected during the workshop synthesised in the taglines is shown in **Fig. 2**. Sub-categories of the model are described below and are based on several rounds of manual coding of the participant responses (Saldana, 2013). The

processed stakeholder input used to generate the model is presented in full in the **Supplementary Material**. The authors acknowledge that 76 stakeholder responses captured during the workshop may not be exhaustive of all viewpoints expressed on the island of Ireland in relation to achieving phosphorus sustainability, and also recognise the need for vital linkages between transition pathways, barriers and enablers when implementing strategies.

3.1. Business-as-usual

This section of the model presents stakeholder perceptions of the current status of phosphorus sustainability on the island of Ireland. Agriculture was identified as a primary consumer of phosphorus and producer of phosphorus-rich wastes. Participants cited issues such as inefficient practices, the prevalence of high phosphorus status soils due to a legacy of phosphorus over-application, and regional manure surpluses, particularly in the dairy sector where intensive systems use high levels of concentrated feedstocks. The agricultural system was described as ‘very leaky’ resulting in overland losses, which combined with soil type, compaction and climactic effects, has created phosphorus lags and legacies in soils that impair water quality and catchment health. The application of recycled phosphorus from waste residues to land as a soil amendment was described as a ‘black box’ in terms of nutrient content and crop bioavailability: this tends to limit the use of such recovered phosphorus sources in favour of traditional well-defined chemical fertilisers.

Participants also identified knowledge gaps around the fragmented collection of agricultural phosphorus monitoring data, particularly in relation to soil testing (approximately only 2% of farms currently test soils (stakeholder participant, pers. comm.)) due to the unwillingness of farmers to invest in testing, especially if they lease their land on a rolling one year contract

known as ‘*conacre*’. A stakeholder noted that ‘*if you don’t measure, you can’t manage*’ and as a result it is difficult to develop plans to manage soil phosphorus when geographical and temporal variations are poorly characterised. Furthermore, there is limited uptake of management practices that could reduce phosphorus consumption on-farm and potentially lower production costs due to poor understanding, awareness and financial support to invest in techniques such as increased forage utilisation and phosphorus loss mitigation strategies.

Participants described phosphorus-related legislation as uncoordinated and noted that current EU Directives focus only on nutrient removal to protect water quality, rather than for recovery and reuse. This is confounded by a lack of regulation ensuring the standardisation of phosphorus products derived from recovered materials, leading to inconsistent performance and difficulties in promoting the benefits of using such products. Furthermore, a lack of incentives constrains uptake and innovation, particularly when chemical fertiliser is considerably cheaper than re-distributed or recovered phosphorus despite the potential vulnerabilities to global phosphorus price and supply shocks. Stakeholders noted that uncertainties exist regarding the most appropriate technology(ies) for phosphorus recovery and recycling, particularly in the waste treatment sector (e.g. sewage sludge, incinerated sewage sludge ash, septic systems and manures). It was also felt that technology adoption is impaired by poor economies of scale at small to medium sized plants, and the concentration of phosphorus needed for cost-effective recovery.

3.2 Drivers of change

Drivers of change are factors which push society to adopt a new paradigm, either by making the current paradigm difficult to maintain or by making a new paradigm more desirable. A key regulatory driver cited by stakeholders in terms of addressing unsatisfactory water quality

was the EU Water Framework Directive. The effective management of waste residues to comply with legislation was also noted as imperative to achieving aspirations for sustainable intensification within the agri-food sector. Participants acknowledged the need to comply with not only current regulation but keep abreast of potential changes and/or new legislation, and the necessary technological advancements required to comply with evolving standards and discharge limits.

A need for standardised technological adoption was flagged as being integral to phosphorus recovery in terms of improving the economics, operational capacity, physical appearance, market appeal and standardisation of recovered products. Several delegates stated that the marketing image of good environmental stewardship was a ‘unique selling point’ for Irish agricultural products and key to the competitiveness of exports, and therefore sustaining this image was critically important in light of plans to encourage growth in this sector (Food Harvest 2020, 2011; Going for Growth, 2013).

Finally, a desire for a phosphorus self-sufficient island was identified as an important emerging driver of change. Participants recognised that the island of Ireland is a net importer of phosphate rock derived chemical fertiliser and is therefore vulnerable to phosphorus supply and price volatility.

3.3. Transformed system

Here stakeholders articulated a future vision for the transformed phosphorus system. A central tenet of the future ‘transformed system’ conceptualised by stakeholders is phosphorus self-sufficiency on the island of Ireland and a highly ambitious target of ‘*near 100% phosphorus recovery*’. Stakeholders envisaged that this has been achieved through a

coordinated approach of recovery for reuse and recycling, made easier by reduced chemical fertiliser usage brought about by import taxation levies and more efficient use. Furthermore, in this future vision, environmental stewardship is a key driving force in consumer decision-making and this, in turn, has led to the widespread adoption of good practices in production systems. Water quality has also improved and legal obligations are being met, which is reflected in reduced eutrophication and pollution, improved aquatic biodiversity and the amenity value of water bodies. In governance of phosphorus, decision and policy makers collaborate on cross-sector and border policy via ‘joined-up’ thinking. Policy approaches are flexible and offer both advice on the uptake of agricultural and industrial practices and innovations, as well as punitive measures for repeatedly failing to meet targets.

A circular phosphorus economy is embedded in the transformed system and waste is now perceived as a resource due to integrated value chains, where materials which were previously considered an undesirable waste substance are now recognised as valuable raw materials that can be processed, packaged and sold. Technologies have been developed to recover not only phosphorus but other nutrients and value-added products, such as biogas or volatile fatty acids, from a single waste stream as part of the bioeconomy. These technologies and innovative solutions for phosphorus recovery from waste residues are suitable for all scales of production, and are widely available and adopted. Targets and incentives for reuse and recycling are established and commonly implemented, and markets are established for standardised recovered products.

Empowered farmers implement knowledge specifically tailored to their precise on-farm requirements. A stakeholder vision articulated during the workshop was a desire for *‘a future where farmers go into the field and apply the right amount of nutrients without problems with*

plant nutrient deficiency and/or environmental issues'. Biophysical science and precision nutrient management, on a field-by-field basis, now dictate best-practice, optimise fertiliser use (organic and inorganic) and mitigate phosphorus loss at source. Nutrient status is optimal for both cropping regime and soil type, facilitated by widespread soil and manure nutrient testing. Precision agriculture and sustainable intensification addresses environmental protection, while balancing profitability and food production. Furthermore, phosphorus management is aligned with existing productivity and environment strategies, and sustainability has been achieved via coordinated, stakeholder-wide approaches. Global knowledge exchange promotes phosphorus best-practice management on the island of Ireland through shared experience and stakeholder empowerment.

3.4. Transition pathways

During the workshop stakeholders identified a number of pathways to transition from the current 'business-as-usual' paradigm to an ideal 'transformed system'. Stakeholders cited incentives as an important and necessary stimulus to drive forward phosphorus reuse and recovery from waste residues, while discouraging the use of virgin phosphate material through a '*tax on imports*'. The need for a non-fragmented approach to sustainability management was also emphasised, and participants called for holistic, cross-border action to develop policy and action plans to implement a nutrient circular economy on the island of Ireland. Central to this is the development of value chains and market opportunities for phosphorus and waste residues through sector-wide cooperation, and the exploration of economic models to support phosphorus reuse, recovery and re-distribution, via implementation of the EU Circular Economy Package (European Commission, 2014) and the proposed new EU Fertilising Products Regulation. To facilitate this, participants felt that there is a need for harmonisation between the capabilities of technologies and end-user

requirements, coupled with increased economic investment for full-scale trials leading to the commercialisation of nutrient recovery systems, alternative fertilisers and soil amendments.

At the farm scale, some participants thought that improved data capture, resolution and analysis are necessary to inform targeted phosphorus mitigation strategies and precision nutrient management at source. Stakeholder examples included '*nutrient re-distribution between farms*', '*better forage utilisation*', the '*ability to access soil legacy phosphorus stores*', transition away from the use of '*splash plate spreading of slurry*' to more nutrient efficient and targeted technologies, and the development of '*alternative fertilisers from recovered phosphorus*' (full details in the **Supplementary Material**). Robust, data-driven practices on-farm will also help address agricultural knowledge gaps, increase efficiencies, and support effective nutrient and waste residue management and re-distribution in an effort to lower chemical fertiliser inputs. The perception of what is a '*good*' fertiliser also needs to be tackled to help create a clearer value proposition and market for waste residues, as well as developing an improved understanding of potential biosecurity risks and their management.

The desire to establish a collaborative all-island nutrient platform, akin to cognate European nutrient platforms, was highlighted by participants as a means to promote stakeholder-wide empowerment in relation to achieving phosphorus sustainability. Key activities suggested for such a network included knowledge exchange, showcasing best-practice, education, raising awareness and changing perceptions, developing value chains and identifying market opportunities for recovered products, as well as acting as an information repository. The use of '*policy champions*' was also advocated by stakeholders as an effective mechanism to drive forward political action on phosphorus sustainability, by improving cross-border communication and breaking down institutional barriers (e.g., disconnection between

regulators and farmers). It was also recognised that collaborative actions need to extend beyond phosphorus and address wider sustainable development goals.

3.5. Barriers and enablers

A number of barriers to implementing an improved phosphorus system on the island of Ireland was identified by stakeholders. An over-arching difficulty cited was the current fragmentation of sustainability initiatives working in isolation rather than cooperating to create a circular economy encompassing many resources. As such, phosphorus sustainability should not be considered separately, but rather as part of wider value chain developments and co-recoverables from waste residues, such as energy, metals, and volatile fatty acids. Short-term cycles of discordant and inflexible regulation were highlighted as a barrier. Examples included the lack of standardisation of recovered products, which inhibits the reuse and therefore recovery of phosphorus, or the enforcement of phosphorus recovery without market development for fertilisers containing recovered phosphorus (or other recovered phosphorus containing products, such as animal feed). Moreover, wastewater industry participants remarked upon the complexities of striving to meet changing, stringent discharge limits to receiving waterbodies in an economic and legislatively compliant way.

Participants noted that negative perceptions of recycled nutrients, such as being ‘contaminated’, discourage the acceptance of recovered nutrients and soil amendments as an alternative to traditional chemical fertilisers. Stakeholders felt that recovery is also hindered by poor understanding of the composition and bioavailability of organic nutrients derived from waste residues, making it difficult to know how much needs to be applied to land and potential impact upon yield.

By far the greatest hurdle identified to achieving phosphorus sustainability on the island of Ireland was the perceived feasibility of recovery. Stakeholders noted at present it is cheaper and easier to import phosphate-based chemical fertiliser rather than recover it from waste streams when the externalities associated with its use fail to be accounted for (e.g. Cordell et al., 2015; Desmidt et al., 2015). Moreover, the size of a wastewater treatment facility must be considered in terms of the cost-effectiveness of currently available technologies for recovery. For example, one technology provider reported servicing global wastewater treatment plant installations varying in capacity from serving 94,000 to 4.5 million people (Ostara, 2018). In the Republic of Ireland the Ringsend wastewater treatment plant in Dublin plans to upgrade to increase the population served to 2.4 million in order to facilitate phosphorus recovery as struvite at similar scales (Irish Water, 2018). However, there are many facilities located on the island of Ireland where capacity is small and also dispersed (e.g., septic systems), and these are not suitable for *in-situ* phosphorus recovery using currently available methods. This highlights the need to develop alternative technologies for phosphorus recovery at smaller scales; in treatment plants serving smaller population sizes, anaerobic digestion units and potentially on-farm or in domestic residences. Concerns were also raised by workshop participants regarding the capabilities of current recovery technologies to comply with stringent discharge limits. It was noted in relation to struvite recovery at wastewater treatment plants that the adoption of such technology is not driven by phosphorus recovery, but rather the financial benefits of preventing unwanted scaling in pipes. Financial incentives and full cost-benefit analysis for phosphorus recovery and infrastructural funding to enable this are therefore paramount to instigating change.

4. Discussion

In this section, we consider similarities and differences around key priorities between the two regions' conceptual models for transformative change (**Table 2**), contextualise our findings in the wider phosphorus landscape, and assess how the model produced for the island of Ireland could effect system-wide sustainability change moving forward.

In the description of 'business-as-usual' the North American and island of Ireland models raised similar issues: they highlighted inefficient phosphorus use, particularly within the agricultural sector, linearity in terms of phosphorus utilisation, poor water quality, and limited recovery due to a lack of incentives, taxes and policy. Interestingly, the North American model noted that on-farm nutrient management plans did commonly exist but often tended to not be implemented. This may relate to state-by-state variation in government approaches ranging from voluntary to mandatory nutrient planning, and additionally the rights of the US farmer to manage their own land (McDowell et al., 2016; Liu et al., 2018). This contrasts with the island of Ireland where it is necessary to have and implement a nutrient management plan if the farm system is derogated under the EU Nitrates Directive (Buckley et al., 2016). Calls have been made for on-farm nutrient management planning to become a mandatory requirement across all farm types and sizes, both in the Republic of Ireland, Northern Ireland and in mainland UK. However, this needs to be implemented in conjunction with improved knowledge transfer between actors (e.g. Micha et al., 2018; Waterton et al., 2018), and supports the need for 'farmer-led knowledge exchange platforms' to promote engagement with soil testing and nutrient management decision making, as highlighted by Daxini et al. (2018).

The island of Ireland model also raised concerns about the unknown crop bioavailability of nutrients from waste residues (such as manures or food waste) and the need for improved

monitoring data in relation to soil testing and fertility management. It is reported in Northern Ireland that ‘less than 10% of farmland has an up-to-date soil analysis’, and that approximately ‘30% of agricultural land is let in conacre’ (a short-term land tenure arrangement between tenants and landowners), which has been suggested to impede long-term land management and planning (A Sustainable Agricultural Land Management Strategy for Northern Ireland, 2016). Moreover, a study in the Republic of Ireland involving a cohort of farmers spanning 12 river catchments in 2010, recorded a 66% adoption rate of soil testing, yet only a 27% usage of nutrient management plans (Buckley et al., 2015). Ambiguity exists regarding national figures for farmer up-take of soil sampling. This further reinforces the need for mandatory nutrient management planning on-farm, which would necessitate regular soil testing for nutrient supply, and facilitate the transformation of current soil phosphorus fertility management strategies towards the delivery of multiple ecosystem services from agricultural systems, as well as mitigating phosphorus losses at source (Macintosh et al., 2019; Macintosh et al., in press) .

Policy silos within government departments were highlighted as ‘business-as-usual’ in the North American model and this too was reflected in the island of Ireland, coupled with the complexities of cross-border collaboration in relation to sustainable phosphorus management, despite both jurisdictions currently operating under EU Directives. In terms of nutrient recovery, both the island of Ireland and North American models highlighted disconnection and uncertainty when selecting the most appropriate technology for phosphorus recovery in a given situation, and the need for economic incentives to stimulate uptake. The complexities of implementing phosphorus recovery resonate across local, national and global scales, and necessitate a ‘roadmap approach’ towards implementation (Mayer et al., 2016).

An important ‘driver of change’ identified in the North America model was the Lake Erie toxic algal bloom in 2014 that temporarily closed the water supply in the town of Toledo, with associated impacts on fisheries and reduced amenities (Jacobs et al., 2017; Steffen et al., 2017). While the occurrence of such severe toxic blooms tends to be less common on the island of Ireland, the driver for water quality improvement is no less important and meeting EU Water Framework Directive targets for achieving ‘good ecological’ status is key. The global impact of phosphorus on water quality through eutrophication and its links to the deterioration of ecosystem services is widely recognised (Dodds et al., 2009; Kleinman et al., 2015; Withers et al., 2015).

A driver distinct to the island of Ireland was the marketing potential of good environmental stewardship and how this can be used as a ‘unique selling point’ for produce from the Republic of Ireland and Northern Ireland. This is particularly important in relation to maintaining and securing new markets as part of agri-food sector plans for intensification, and of paramount importance to Northern Ireland produce, particularly post-Brexit. Both models emphasised national dependency on imported phosphorus and acknowledged the need for sustainable management and recovery to ensure resilience to potential supply and price fluctuations. This is particularly prudent on the island of Ireland which has no active phosphate rock reserves and so is a net importer of phosphorus, in contrast to the US which produces the majority of its phosphorus domestically (US Geological Survey, 2018).

The ‘transformed system’ conceptualised by the two models is underpinned by a strong desire for a phosphorus circular economy and phosphorus self-sufficiency. While a general desire for regional self-sufficiency may be viewed as somewhat ‘inward looking’ given the inter-connectivity of world trade, with respect to phosphorus access, stakeholders’ preference

for sufficient level of national security serves to highlight the implications of potential insecurities and risks of phosphorus price and supply shocks, and disruptions for food production (Cordell et al., 2015).

Consensus does exist between the two models on how best to achieve transformation. Key similarities included: incentivisation; integrated value chains to drive the reuse of wastes; improved knowledge of soil health and on-farm nutrient management; precision farming; effective governance and reduced consumption of virgin materials. The North American model further articulated a phosphorus future with sustainable consumer diets with low phosphorus footprints and public awareness of the role phosphorus plays in society and the environment. In contrast, the island of Ireland model described societal changes as a pathway rather than a ‘future state’: education and societal awareness, for example, is to be fostered through science gallery exhibits and documentaries to promote shared equity in terms of phosphorus impact on the environment.

Unique to the the island of Ireland’s ‘transformed system’ was environmental acumen driving consumer decision-making and promoting best-practice in production systems. This again links to the desire for Irish produce to have a strong brand focus, both domestically and internationally thereby increasing export demand. This is reflected in the prevalence of Irish farmers signing up to quality assurance schemes such as Bord Bia’s Origin Green sustainability programme (in the Republic of Ireland) and the Red Tractor or Farm Quality Assurance Scheme (in Northern Ireland). Such schemes afford farmers the advantage of ‘value added product’ to reward good farming credentials and promote the quality of Irish produce world-wide.

Also specific to the island of Ireland was the need for decision and policy makers to collaborate cross-border via ‘joined-up’ thinking. In the island of Ireland workshop there was regular debate by stakeholders surrounding the complexities of developing phosphorus sustainability across the political regions. While in the North American workshop there was little discussion of the challenges of coordinating phosphorus sustainability across these two nations. This may in part be attributed to the lower representation of Canadian stakeholders compared to US stakeholders in the workshop (see Jacobs et al., 2017 for specific stakeholder numbers). It may also be due to the relative importance of cross-border trade/dialogue between the Republic of Ireland and Northern Ireland (compared to North American countries), however the latter was not explicitly discussed in either workshop. The intricacies of such cross-jurisdiction management were seen as a potential barrier to phosphorus sustainability on the island of Ireland, particularly in relation to Brexit, and the future challenges associated with this. For example, the potential divergence of legislation in Northern Ireland and the UK from that followed by the Republic of Ireland and the remaining EU member states. The implications of Brexit forecast for the Republic of Ireland include possible disruption to the UK market and imposition of tariff barriers with increased regulation for agri-food trade flows, which could potentially stifle future synergies relating to phosphorus sustainability across the island of Ireland (Irish Farmer’s Association, 2017).

Of note in the North American ‘transition pathways’, participants recorded progress to-date in relation to the identified pathways (Jacobs et al., 2017). These included: advances in improving soil health knowledge through so called ‘legacy’ phosphorus management and policy (Haygarth et al., 2014; Rowe et al., 2016); the work of the International Plant Nutrient Institute in the US on judicious plant nutrition (Bruulsema et al., 2009); significant financial investment by the Water Environment Research Foundation in technology innovation and

adoption in response to demand from wastewater utilities; and the use of ‘community-policy-science networks’ such as the Sustainable Phosphorus Alliance as a forum to promote sustainability via stakeholder engagement, raising awareness and promoting behavioural change (Sustainable Phosphorus Alliance, 2018). In the island of Ireland model, collaborative networks were highlighted as a need and an important transition pathway to effect change, as well as nurturing a circular phosphorus economy through policy and incentives, value chains, and market development for recovered product. However, unlike the North American model such networks have yet to be significantly developed on the island of Ireland.

At the all-island workshop, stakeholders noted the need for nutrient re-distribution to address regional imbalances in phosphorus supply and demand (this is of particular relevance between intensive dairy and tillage systems in Northern Ireland, and the forestry sector in the Republic of Ireland, which is generally considered nutrient poor), and the desire for data-informed practices on-farm to mitigate phosphorus losses and improve efficiencies. Nutrient re-distribution was also noted by stakeholders in the North American model, particularly in the context of concentrated animal production areas (Jacobs et al., 2017; Liu et al., 2018). The need to mitigate phosphorus losses to water on-farm has been recognised as an emerging research area by the Department of Agriculture, Food and the Marine in the Republic of Ireland. Another important island of Ireland ‘transition pathway’ was harmonisation of the capabilities of new and emerging recovery technologies with end-user requirements, in combination with increased investment for full-scale trials leading to commercial adoption. In contrast with viewpoints expressed in the North American workshop, stakeholders noted a lack of investment in wastewater infrastructure on the island of Ireland to develop recovery.

A principal barrier to change revealed by the North American model was the current low market price of phosphate rock, which dis-incentivises judicious use and financial investment into technological developments in the field of phosphorus recovery. Furthermore, the low cost of newly mined material serves only to stifle policy innovations and the implementation of incentives to promote adoption. A lack of technological readiness and economic viability were also cited as reasons for low uptake of phosphorus recovery. Similar economic and policy barriers also held true for the island of Ireland. To address this, stakeholders emphasised the need to integrate phosphorus sustainability initiatives and recovery practices into wider value chain developments and consider co-recoverables as part of the circular and bioeconomy. Short-term cycles of discordant and inflexible regulation were also highlighted as a barrier. Island of Ireland stakeholders called for regulatory harmonisation to facilitate recovery for reuse in agriculture through the standardisation of recovered products. Current on-going revisions to the EU Fertilisers Regulation will be key to addressing this through the adoption of CE-marking for recovered struvite and phosphate salts, recycling of ashes and for biochar (European Sustainable Phosphorus Platform, 2017); however, much scope still exists in relation to organic wastes and soil conditioners. Negative perceptions surrounding recovered and recycled nutrient products also need to be overcome to encourage uptake (Metson et al., 2018).

5. Conclusion

Decades of fertiliser over use in the agri-environment, coupled with the production of nutrient-rich waste residues linked to an expanding human population (e.g., sewage and industrial effluents) have resulted in the widespread phosphorus enrichment of receiving ecosystems and the accumulation of ‘legacy’ phosphorus in soils and sediments (Withers et al., 2015; Rowe et al., 2016; Macintosh et al., in press). Moving forward, the challenge is to

615 produce enough food to meet rising global demands while protecting water and
616 environmental quality, and seeking to manage uncertainty around potential future phosphorus
617 price or supply shocks, as well as adapting to climatic extremes. To address these challenges,
618 across local, national and global scales, a holistic approach to phosphorus management and
619 policy development should be a central principle towards implementing wider societal
620 stewardship. The transformational change model produced in this study, and for North
621 America, offers a stakeholder-led ‘guiding vision’ (Spath and Rohrer, 2010) towards
622 achieving wider phosphorus sustainability. Of note is that while all efforts were made to
623 ensure a representative mix of stakeholders attended both workshops, it is unrealistic to
624 expect that this process will have exhaustively captured all viewpoints existing in both
625 regions. The mechanisms to validate and incorporate such models into existing policy
626 structure and management frameworks are therefore an area requiring further consideration.
627
628 In an effort to bring about change, collaborative, stakeholder-led nutrient platform networks
629 have emerged in Europe and globally as a tool to bring together disparate actors to address
630 region-specific nutrient sustainability issues: examples include the European Sustainable
631 Phosphorus Platform and the Baltic Sea Action Group in Europe, and the Sustainable
632 Phosphorus Alliance in the United States. Wide ranging engagement in, and between, such
633 networks is suggested to facilitate knowledge exchange among diverse sectors and help
634 promote current best-practice and awareness building, while supporting and embedding
635 behavioural change. Although establishing such networks does not necessarily guarantee
636 outcomes, and the success of such networks can be difficult to ascertain (e.g. Kusters et
637 al., 2018), they are playing a pivotal role in raising the profile of phosphorus sustainability
638 initiatives and practices, and provide an effective forum for dialogue with policy makers.
639 The formation of such a network on the island of Ireland, provides opportunity for a cross-

border coalition to drive forward a phosphorus circular economy and help deliver on wider global policy such as the United Nations sustainable development goals (United Nations, 2015). Moreover, the monetary value of ecosystem services and biodiversity in the Republic of Ireland has been estimated at over €2.6 billion per year, which further supports the economic and environmental need to protect such systems from nutrient enrichment (DCCAE, 2012). In New Zealand, environmental degradation places at risk an \$18 billion (NZD) tourist industry, which further supports the need for nutrient management to achieve water quality goals, as well as considering the wider impacts of anthropogenic activity in terms of attaining sustainable agricultural productivity within environmental constraints (Ministry for the Environment, 2007; McDowell et al., 2018.). In the United States, freshwater eutrophication is estimated to cost a minimum of \$2.2 billion (USD) every year (Diaz and Rosenberg, 2008; Dodds et al., 2009). These examples serve to illustrate the potential global cost of phosphorus pollution.

The model of transformative change produced in this paper provides a conceptual regional framework for phosphorus sustainability on the island of Ireland, with dual benefits for both water quality and food security. It presents a coherent synthesis of stakeholder views, which could be used to inform strategic policy and develop collaborative solutions across diverse sectors. Furthermore, it offers scope for expansion beyond phosphorus to other co-recoverables as part of wider circular and bioeconomy developments on the island of Ireland to ensure environmental protection, resource security and sustainable economic growth (Government of Ireland, 2018). Many of the transitional pathways presented by both models, for example, implementing phosphorus management practices on-farm, incentivising recovery and technology adoption, and developing collaborative networks and value chains for recovered products, resonate globally and are highly pertinent to other jurisdictions.

Further, the participatory process used here (and in North America) can be applied in other countries or regions to develop regional phosphorus transformational models of change.

Acknowledgements

Any views expressed here are those of the authors and our interpretation of stakeholder views, and do not necessarily reflect those of the organisations with which they are affiliated. We acknowledge the Environmental Protection Agency of Ireland, Science Foundation Ireland, the Department for the Economy (in Northern Ireland), and the Microbiology Society (Charity No: 264017 and SC039250). We thank the National Science Foundation's Phosphorus Research Coordination Network run by Arizona State University (Award 1230603), where discussions on this research and article occurred. We thank session chairs, Professor Richard McDowell, Dr Paul Butler and Professor Philip Haygarth. Thanks are also extended to the 'All-Island Phosphorus Sustainability' workshop participating stakeholders, table facilitators, note-takers, and workshop contributors.

Supplementary Material

The Supplementary Material includes: 1. keynote speaker and panel member presentation topics at the 'All-Island Phosphorus Sustainability' workshop; 2. detailed elements of the transformational change model and stakeholder questions used during the workshop to prompt breakout group discussion; and 3. processed stakeholder comments and perspectives captured at the 'All-Island Phosphorus Sustainability' workshop.

References

- Agricultural Catchments Programme (ACP) Phase 2 Report February. 2017. Teagasc, Johnstown Castle Environment Research Center, 2017, pp. 145.
<https://www.teagasc.ie/media/website/environment/water-quality/Draft-Agricultural-Catchments-Programme-Phase-2-Report.pdf>.
- A Sustainable Agricultural Land Management Strategy for Northern Ireland. 2016. Expert Working Group on Sustainable Land Management. Department of Agriculture, Environment and Rural Affairs, pp. 131. ISBN 978-1-84807-708-9.
<https://www.daera-ni.gov.uk/publications/sustainable-agricultural-land-management-strategy-report-and-executive-summary>.
- Bruulsema, T., Lemunyon, J., Herz, B. 2009. Know your fertilizer rights. Crops and Soils. 42, 13-16.
- Buckley, C., Howley, P., Jordan, P. 2015. The role of differing farming motivations on the adoption of nutrient management practices. International Journal of Agricultural Management. 4, 152-162.
- Buckley, C., Wall, D. P., Moran, B., O'Neill, S., Murphy, P.N.C. 2016. Phosphorus management on Irish dairy farms post controls introduced under the EU Nitrates Directive. Agricultural Systems. 142, 1-8.

Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., Young,
O. 2006. Scale and cross-scale dynamics: governance and information in a multilevel world.
Ecology and Society. 11(2), 8.

Cordell, D., Drangert, J.-O., White, S. 2009. The story of phosphorus: Global food security
and food for thought. Global Environmental Change. 19, 292-305.

Cordell, D., Metson, G., Iwaniec, D., Bui, T., Childers, D., Dao, N., Dang, H., Davidson, J.,
Jacobs, B., Kumwenda, S., Morse, T., Nguyen, V., Thole, B., Tilley, E. 2016. Transforming
Cities: Securing food and clean waterways through a transdisciplinary phosphorus approach,
in Part 3, 'Transdisciplinary Research and Practice for Sustainable Outcomes', (eds.) Fam,
D., Mitchell, C., Riedy, C. Palmer, J. Routledge, UK.

Cordell, D., Mikhailovich, N., Mohr, S., Jacobs, B., White, S. 2014. Adapting to future
phosphorus scarcity: investigating potential sustainable phosphorus measures and strategies.
Phase II of the Australian Sustainable Phosphorus Futures project, prepared by Institute for
Sustainable Futures, University of Technology, Sydney, for the Rural Industries Research and
Development Corporation, Australian Government, Canberra.

<https://agrifutures.infoservices.com.au/items/14-039>

Cordell, D., Turner, A., Chong, J. 2015. The hidden cost of phosphate: Mapping the
sustainability impacts and risks of phosphate fertilisers along the supply chain from
extraction to the dinner table. Global Change, Peace and Security. 27, 323-343, Special Issue.

Cordell, D., White, S. 2014. Life's bottleneck: sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources*. 39, 161-188.

Daxini, A., O'Donoghue, C., Ryan, M., Buckley, C., Barnes, A.P., Daly, K. 2018. Which factors influence farmers' intentions to adopt nutrient management planning? *Journal of Environmental Management*. 244, 350-360.

Department of Communications Climate Action and Environment. 2012. Our sustainable future: A framework for sustainable development for Ireland.

[https://www.dccae.gov.ie/documents/Our Sustainable Future - 2012.pdf](https://www.dccae.gov.ie/documents/Our_Sustainable_Future_-_2012.pdf)

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B. 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. *Critical Reviews in Environmental Science and Technology*. 45(4), 336-384.

Diaz, R.J., Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. *Science*, 321 (5891), 926–929. DOI 10.1126/science.1156401.

Dinesh, D., Zougmore, R., Vervoort, J., Totin, E., Thornton, P., Solomon, D., Shirsath, P.B., Pede, V.O., Lopez-Noriega, I., Läderach, P., Korner, J., Hegger, D., Girvetz, E.H., Friis, A.E., Driessen, P.P.J., Campbell, B.M. 2018. Facilitating change for climate-smart agriculture through science-policy engagement. *Sustainability*. 10(8), 2616.

Dodds, W.K., Bouska, W.W., Eitzmann, J.L., Pilger, T.J., Pitts, K.L., Riley, A.J., Schloesser, J.T., Thornbrugh, D.J. 2009. Eutrophication of U.S. freshwaters: Analysis of potential economic damages. *Environmental Science and Technology*. 43(1), 12-19.

Edelenbos, J., Van Buuren, A., van Schie, N. 2011. Co-producing knowledge: joint knowledge production between experts, bureaucrats and stakeholders in Dutch water management projects. *Environmental Science and Policy*. 14(6), 675-684.

Elser, J., Bennett, E. 2011. Phosphorus cycle: A broken biogeochemical cycle. *Nature*. 478, 29-31.

European Commission, 2014. Towards a Circular Economy: A Zero Waste Programme for Europe. European Commission, Brussels.

European Sustainable Phosphorus Platform. 2017. STRUBIAS proposals for EU Fertilisers Regulation. ESPP eNews no. 15. <https://phosphorusplatform.eu/scope-in-print/enews/1540-enews15>

Food Harvest 2020. 2011. Department of Agriculture, Food and the Marine. <https://www.agriculture.gov.ie/publications/2011/annualreviewandoutlookforagriculturefisheriesandfood20102011/nationaldevelopments/foodharvest2020/>

Gilbert, N. 2009. The Disappearing Nutrient. *Nature*. 461, 716-718.

781 Going for Growth. 2013. A strategic action plan in support of the Northern Ireland agri-food
782 industry. Agri-Food Strategy Board, Northern Ireland.
783 <https://www.farminguk.com/content/knowledge/Going-for-Growth-Northern-Ireland-agri->
784 [food-industry-report\(9347-3773-3943-4304\).PDF](https://www.farminguk.com/content/knowledge/Going-for-Growth-Northern-Ireland-agri-food-industry-report(9347-3773-3943-4304).PDF)
785
786 Government of Ireland. 2018. National Policy Statement on the Bioeconomy, pp. 20. ISBN -
787 S130/07/43/0004.
788
789 Haygarth, P., Jarvie, H., Powers, S., Sharpley, A., Elser, J., Shen, J., Peterson, H., Chan,
790 N., Howden, N., Burt, T., Worrall, F., Zhang, F., Liu, X. 2014. Sustainable phosphorus
791 management and the need for a long-term perspective: the legacy hypothesis.
792 Environmental Science and Technology. 48, 8417-8419.
793
794 Irish Farmer's Association. 2017. Brexit: The Imperatives for Irish Farmers & the Agri-Food
795 Sector. IFA Policy Paper, March 2017, pp. 44.
796
797 Irish Water. 2016. National Wastewater Sludge Management Plan. 112 pp. Dublin, Ireland.
798 [https://www.water.ie/projects-plans/our-plans/wastewater-sludge-management/Final-](https://www.water.ie/projects-plans/our-plans/wastewater-sludge-management/Final-NWSMP.pdf)
799 [NWSMP.pdf](https://www.water.ie/projects-plans/our-plans/wastewater-sludge-management/Final-NWSMP.pdf)
800
801 Irish Water. 2018. Ireland-Cork: Wastewater treatment plant construction work 2018/S 078-
802 175026. [https://ted.europa.eu/TED/notice/udl?uri=TED:NOTICE:175026-](https://ted.europa.eu/TED/notice/udl?uri=TED:NOTICE:175026-2018:TEXT:EN:HTML)
803 [2018:TEXT:EN:HTML](https://ted.europa.eu/TED/notice/udl?uri=TED:NOTICE:175026-2018:TEXT:EN:HTML) (accessed 20.10.18).
804

805 Iwaniec, D., Metson, G., Cordell, D. 2016. P-FUTURES: Towards urban food and water
806 security through collaborative design and impact. *Current Opinion in Environmental*
807 *Sustainability*. 20, 1-7. Special Issue on co-design and co-production of transformative
808 knowledge.

809

810 Jacobs, B., Cordell, D., Chin, J. and Rowe, H. 2017. Towards phosphorus sustainability in
811 North America: A model for transformational change. *Environmental Science and Policy*. 77,
812 151-159.

813

814 Jacobs, B., Lee, C., Watson, S., Dunford, S., Coutts-Smith, A. 2016. Adaptation planning
815 process and government adaptation architecture support regional action on climate change in
816 New South Wales, Australia. In: Filho, W.L., (Ed.), *Innovation in Climate Change*
817 *Adaptation*. Springer International Publishing, Switzerland, pp. 17-29.

818

819 Kemp, R., Rotmans, J. 2005. The management of the co-evolution of technical,
820 environmental and social systems. *Towards Environmental Innovation Systems*, 33-55.

821

822 Kleinman, P.J.A., Sharpley, A.N., Withers, P.J.A., Bergström, L., Johnson, L.T., Doody, D.
823 G. 2015. Implementing agricultural phosphorus science and management to combat
824 eutrophication. *Ambio*. 44 (2), 297–310. DOI 10.1007/s13280-015-0631-2.

825

826 Kusters, K., Buck, L., de Graaf, M., Minang, P., van Oosten, C., Zagt, R. 2018. Participatory
827 planning, monitoring and evaluation of multi-stakeholder platforms in integrated landscape
828 initiatives. *Environmental management*. 62(1), 170-181.

829

830 Levin, K., Cashore, B., Bernstein, S., Auld, G. 2007. February. Playing it forward: Path
831 dependency, progressive incrementalism, and the ‘Super Wicked’ problem of global climate
832 change. In International Studies Association 48th Annual Convention. Chicago.
833

834 Liu, J., Kleinman, P.J.A., Aronsson, H., Flaten, D., McDowell, R.W., Bechmann, M., Beegle,
835 D.B., Robinson, T.P., Bryant, R.B., Liu, H., Sharpley, A.N., Veith, T.L. 2018. A review of
836 regulations and guidelines related to winter manure application. *Ambio*.
837 DOI:10.1007/s13280-018-1012-4.
838

839 Micha, E., Roberts, W., Ryan, M., O’Donoghue, C., Daly, K. 2018. A participatory approach
840 for comparing stakeholders’ evaluations of P loss mitigation options in a high ecological
841 status river catchment. *Environmental Science and Policy*. 84, 41-51.
842

843 Macintosh, K.A., Doody, D.G., Withers, P.J.A., McDowell, R.W., Smith, D.R., Johnson,
844 L.T., Bruulsema, T.W., O’Flaherty, V., McGrath, J.W. 2019. Transforming soil phosphorus
845 fertility management strategies to support the delivery of multiple ecosystem services from
846 agricultural systems. *Science of the Total Environment*, 649, 90-98.
847

848 Macintosh, K.A., Mayer, B.K., McDowell, R.W., Powers, S.M., Baker, L.A., Boyer, T.H.
849 and Rittmann, B.E. (in press). Managing diffuse phosphorus at the source versus at the sink.
850 *Environmental Science and Technology*. DOI: 10.1093/est/36.3.287.
851

852 Mayer, B.K., Baker, L.A., Boyer, T.H., Drechsel, P., Gifford, M., Hanjra, M.A.,
853 Parameswaran, P., Stoltzfus, J., Westerhoff, P., Rittmann, B.E. 2016. Total value of

854 phosphorus recovery. *Environmental Science and Technology*. 50, 6606–6620. DOI
855 10.1021/acs.est.6b01239.

856

857 McDowell, R.W., Dils, R.M., Collins, A.L., Flahive, K.A., Sharpley, A.N., Quinn, J. 2016. A
858 review of the policies and implementation of practices to decrease water quality impairment
859 by phosphorus in New Zealand, the UK, and the US. *Nutrient Cycling in Agroecosystems*.
860 104, 289-305.

861

862 McDowell, R.W., Snelder, T., Harris, S., Lilburne, L., Larned, S.T., Scarsbrook, M., Curtis,
863 A., Holgate, B., Phillips, J., Taylor, K. 2018. The land use suitability concept: Introduction
864 and an application of the concept to inform sustainable productivity within environmental
865 constraints. *Ecological Indicators*. 91, 212-219.

866

867 McGrath, J.W., O’Flaherty, V. 2014. P from Wastewaters project; Grant Number 2014-W-
868 LS-7, Environmental Protection Agency of Ireland.

869

870 McGrath, J.W., O’Flaherty, V. 2015. i–PAD: Innovative biological phosphate and anaerobic
871 digestion technology for waste treatment, energy generation and phosphorus recovery
872 project; Science Foundation Ireland and the Department for the Economy (Northern Ireland).

873

874 McNie, E.C., Parris, A., Sarewitz, D. 2016. Improving the public value of science: A
875 typology to inform discussion, design and implementation of research. *Research Policy*.
876 45(4), 884-895.

877

878 Metson, G.S., Powers, S.M., Hale, R.L., Sayles, J.S., Öberg, G., MacDonald, G.K.,
879 Kuwayama, Y., Springer, N.P., Weatherley, A.J., Hondula, K.L., Jones, K, Chowdhury, R.B.,
880 Beusen, A.H.W., Bouwman, A.F. 2018. Socio-environmental consideration of phosphorus
881 flows in the urban sanitation chain of contrasting cities. *Regional Environmental Change*,
882 18(5), 1387-1401.

883

884 Ministry for the Environment. 2007. Value of the environment to the economy. In
885 Environment New Zealand; Ministry for the Environment: Wellington, New Zealand, p. 45-
886 46.

887

888 O'Reilly, M., Parker, N. 2013. 'Unsatisfactory Saturation': A critical exploration of the notion
889 of saturated sample sizes in qualitative research. *Qualitative Research*. 13(2), 190-197.
890 <https://doi.org/10.1177/1468794112446106>.

891

892 Ostara. 2018. Nutrient Management Solutions: Ostara's award-winning nutrient recovery
893 technology is a sustainable solution to global nutrient issues. [http://ostara.com/wp-](http://ostara.com/wp-content/uploads/2018/09/EU-Handout-Ostara-Overview.pdf)
894 [content/uploads/2018/09/EU-Handout-Ostara-Overview.pdf](http://ostara.com/wp-content/uploads/2018/09/EU-Handout-Ostara-Overview.pdf) (accessed 20.10.18).

895

896 Pohl, C. 2008. From science to policy through transdisciplinary research. *Environmental*
897 *Science and Policy*. 11(1), 46-53.

898

899 Polk, M. 2015. Transdisciplinary co-production: Designing and testing a transdisciplinary
900 research framework for societal problem solving. *Futures*, 65, 110-122.

901

902 Reijnder, L. 2014. Phosphorus resources, their depletion and conservation, a review.
 903 Resources, Conservation and Recycling. 93, 32-49.
 904
 905 Rowe, H., Withers, P.J., Baas, P., Chan, N.I., Doody, D., Holiman, J., Jacobs, B., Li, H.,
 906 MacDonald, G.K., McDowell, R., Sharpley, A.N. 2016. Integrating legacy soil phosphorus
 907 into sustainable nutrient management strategies for future food, bioenergy and water security.
 908 Nutrient Cycling Agroecosystems. 104, 393-412.
 909
 910 Saldana, J. 2013. An Introduction to Codes and Coding, in 'The Coding Manual for
 911 Qualitative Researchers', 2nd ed., pp. 1-40. Los Angeles: SAGE.
 912
 913 Schröder, J.J., Cordell, D., Smit, A.L., Rosemarin, A. 2010. Sustainable Use of Phosphorus,
 914 prepared for European Union tender project ENV.B.1/ETU/2009/0025. Report 357, Plant
 915 Research International, Wageningen University and Research Centre, Wageningen, 122 pp.
 916
 917 Schulte, R.P.O., Doody, D.G., Byrne, P., Cockerill, C., Carton, O.T. 2009. Lough Melvin:
 918 Developing cost-effective measures to prevent phosphorus enrichment of a unique aquatic
 919 habitat. Tearmann: Irish Journal of Agri-environmental Research. 7, 1-18.
 920
 921 Sharpley, A., Jarvie, H., Flaten, D., Kleinman, P. 2018. Celebrating the 350th Anniversary of
 922 Phosphorus Discovery: A Conundrum of Deficiency and Excess. Journal of Environmental
 923 Quality. 47, 774-777. DOI:10.2134/jeq2018.05.0170.
 924
 925 Späth, P., Rohrer, H. 2010. 'Energy transitions': The transformative power of regional
 926 discourse on socio-technical futures. Research Policy. 39, 449-458.

927

928 Stahel, W.R. 2016. Circular Economy: A new relationship with our goods and materials
 929 would save resources and energy and create local jobs. *Nature*. 531, 435-438.
 930

931 Steffen, M.M., Davis, T.W., McKay, R.M.L., Bullerjahn, G.S., Krausfeldt, L.E., Stough,
 932 J.M., Neitzey, M.L., Gilbert, N.E., Boyer, G.L., Johengen, T.H. Gossiaux, D.C. 2017.
 933 Ecophysiological examination of the Lake Erie microcystis bloom in 2014: linkages between
 934 biology and the water supply shutdown of Toledo, OH. *Environmental Science and*
 935 *Technology*. 51, 6745-6755.
 936

937 Sustainable Phosphorus Alliance. 2018. <https://phosphorusalliance.org/> (accessed 25.17.18)
 938

939 Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S. 2002. Agricultural
 940 sustainability and intensive production practices. *Nature*. 418(6898), 671.
 941

942 United Nations. 2015. Transforming our world: the 2030 Agenda for Sustainable
 943 Development. United Nations General Assembly
 944 <https://www.un.org/sustainabledevelopment/>
 945

946 U.S. Geological Survey. 2018. Mineral commodity summaries 2018: U.S. Geological Survey,
 947 200 p., <https://doi.org/10.3133/70194932>.
 948

949 van der Molen, F. 2018. How knowledge enables governance: The coproduction of
 950 environmental governance capacity. *Environmental Science and Policy*. 87, 18-25.
 951

952 van Dijk, K.C.; Lesschen, J.P.; Oenema, O. 2016. Phosphorus flows and balances of the
 953 European Union Member States. *Science of the Total Environment*. 542, 1078-1093.
 954

955 van Kauwenbergh, S.J. 2010. World phosphate reserves and resources. IFDC, Washington
 956 D.C., USA.
 957

958 Villalba, G., Liu, Y., Schroder, H., Ayres, R.U. 2008. Global phosphorus flows in the
 959 industrial economy from a production perspective. *Journal of Industrial Ecology*. 12, 557-
 960 569.
 961

962 Waterton, C., Norton, L., Cardwell, E., Chadwick, D., Gibbons, J., Macintosh, K.A,
 963 Sakrabani, R., Shrestha, S. 2018. Slurry-Max: Holistic decision support for cattle slurry
 964 storage and treatment. Sustainable Agriculture Research and Innovation Club (SARIC)
 965 Technical Report.
 966

967 Withers, P.J.A., van Dijk, K.C., Neset, T.S.S., Nesme, T., Oenema, O., Rubæk, G.H.,
 968 Schoumans, O.,F., Smit, B., Pellerin, S. 2015. Stewardship to tackle global phosphorus
 969 inefficiency: The case of Europe. *Ambio* 44 (2), 193-206.
 970

971 Withers, P.J.A., Neal, C., Jarvie, H.P.; Doody, D.G. 2014. Agriculture and eutrophication:
 972 Where do we go from here? *Sustainability*. 6, 5853-5875.

973

974 **Fig. 1.** Conceptual model of transformative change (adapted from Jacobs et al., 2016; 2017).

Fig. 2. Transformational change model for phosphorus sustainability on the island of Ireland.

Table 1. Stakeholder numbers and sector at the ‘All-Island Phosphorus Sustainability’ workshop.

Affiliation category	Number of participants		
	Republic of Ireland	Northern Ireland	Outside
Academic	10	15	9
Government agency	5	14	0
Research institute	4	1	1
Water utility company	1	3	0
Phosphorus recycling company	0	0	4
Profit industry	2	2	1
Non-profit organisation	3	0	1

980 **Table 2.** Similarities and differences between transformational change models for the island of Ireland and North America.

Both models		
Similarities	✓	Inefficient and linearity of phosphorus use
	✓	Poor water quality
	✓	Limited recovery due to lack of incentives, taxes and policy
	✓	Policy silos and short-term cycles of discordant and inflexible regulation impede progress
	✓	Dependency on imported phosphorus
	✓	A desire for a phosphorus circular economy and self-sufficiency
	✓	Need for incentivisation and integrated value chains to drive the reuse of wastes
	✓	Need for improved knowledge of soil health and on-farm nutrient management; adoption of precision farming
	✓	Call for effective governance
	✓	Reduced consumption of virgin materials
	✓	A need for nutrient re-distribution to address regional imbalances
	✓	Low market price of phosphate rock dis-incentivises judicious use and financial investment in recovery technologies
	✓	Economic and policy barriers
	✓	Phosphorus sustainability initiatives and recovery practices need to be integrated into wider value chain developments
	✓	Need to overcome negative perceptions of recovered and recycled nutrient products to encourage uptake
Island of Ireland		North America
Differences	x	Complexities of cross-border collaboration and Brexit
	x	Uncertainty surrounding nutrient bioavailability from waste residues
	x	Need for regular soil testing and nutrient management planning
	x	Uncertainty when selecting most appropriate technology for recovery
	x	Marketing potential of good environmental stewardship recognised
	x	Environmental acumen driving consumer decision-making and best-practice in production systems
	x	No active phosphate rock reserves
	x	Establishment of a collaborative nutrient highlighted as a need
	x	Phosphorus loss mitigations needed on-farm
	x	Harmonisation of recovery technologies with end-user needs
	x	Investment for full-scale trials leading to commercial adoption
	x	Regulatory harmonisation to facilitate recovery for reuse in agriculture through the standardisation of recovered products
	x	State-by-state regulatory system
	x	Toxic algal blooms impacting drinking water supply
	x	Domestic phosphate rock reserves
	x	Sustainable consumer diets with low phosphorus footprints
	x	Public awareness of the role phosphorus plays in society and the environment
	x	Sustainable Phosphorus Alliance established as a ‘community-policy-science network’

981