Science of the Total Environment 785 (2021) 147251

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An overview on deficit and requirements of the Irish national soil phosphorus balance

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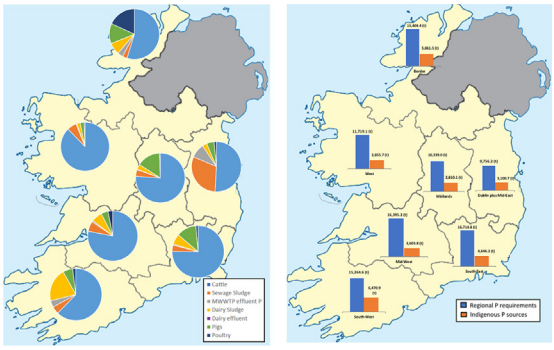
HIGHLIGHTS

- 62.8% of Irish agricultural land has agronomically suboptimal P levels.
- 43,000 t of imported P fertilisers are annually applied to Irish agricultural land.
- 95,500 t of P are required annually to sustain crop production and build soil P.
- Cattle produce the largest quantity of indigenous P annually at 19,300 t.
- Ireland produces 30% of its P requirements from indigenous sources.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 March 2021
Received in revised form 15 April 2021
Accepted 16 April 2021
Available online 22 April 2021

Editor: Fernando A.L. Pacheco

Keywords:
Phosphorous
Phosphorous recycling
Soil phosphorous requirements
Regional phosphorous sources

ABSTRACT

Phosphorus (P) is an essential life-supporting nutrient for which there is no substitute. Modern farming practice and food production are supported by the application of mineral P fertiliser derived from finite mined phosphate rock. The European Union does not have indigenous mineral phosphate reserves, which poses a significant issue to food security. This research paper assesses the potential of indigenous recycled P sources to replace imported P fertiliser within the Republic of Ireland. The research is undertaken at NUTS 3 (Nomenclature of Territorial Units) regional level, the nutrient soil P requirement is established, and the extent to which the regional production of indigenous recycled P sources can offset this requirement is determined. The soil P requirement was derived from analyzing the regional soil P indexes, stocking rate and land-use. It was established that to optimise Irish agricultural production, approximately 95,500 t of P fertiliser is required by Irish agriculture per annum. Indigenous P sources were reviewed to determine their contribution to the Irish P balance; the sources included sewage sludge, dairy processing waste, and animal manures. Regional indigenous P quantities vary greatly with the South-West Region producing the largest quantity of indigenous recycled P at 42.4% of required P than the Mid-West Region only producing 22.0% of its P requirement indigenously. Sources of indigenous P also vary greatly from region to region depending on population and industry, with the highest quantity of sewage sludge being produced in the Dublin plus Mid-East Region while the greatest contributor of dairy waste is the South-West Region. In total, over 28,500 t of P is recovered from indigenous sources per annum. This indicates that approximately 30% of the national P requirement could be met by indigenous P recycling.

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https://doi.org/10.1016/j.scitotenv.2021.147251

1. Introduction

1.1. Phosphorous demand in Ireland

Phosphorus (P) is a naturally occurring finite mineral, regarded as a vital building block used in the growth and reproduction of all living organisms. Cordell and White (2011) note that the intensification of agricultural production over the past 70 years has revolutionized farming practice; this shift has led to applying artificial mineral P fertilisers to replace P removed by crop harvests. The application of mineral fertilisers has become an integral part of modern agriculture and is vital to sustain modern farming practices and food production. Mineral P fertilisers are generally produced by processing P rich rock (phosphate rock) which is found "*at the surface of the earth's crust and is finite and non-renewable*" (Ryan et al., 2014). The majority of world phosphate rock reserves are located in Morocco and Western Sahara. The North Western Region of Europe (NWE) does not have a substantial P rock supply (Jasinski, 2019). The European Union recognized this and added phosphate rock to its critical raw material list in 2014 (EU, 2014) and white phosphorous to the list in 2017 (EU, 2017).

In 2015 it was estimated that Ireland was the ninth-largest fertiliser consumer of all EU member states, with a total of 146.4 kg of artificial fertiliser applied per hectare of agricultural land, of which 4.2 kg was P (EEA, 2015). In the same period, 36,551 t of phosphorus fertiliser was sold to Irish agriculture, an increase of 2.7% on the previous year (Dillon et al., 2017).

The majority of chemical fertilisers used in Ireland are imported, with an estimated value of €373 million in 2017 (CSO a, 2019). The imported P fertilisers were applied to grassland and crops over an estimated 4.4 million hectares of agricultural land, of which grass is the main crop (80.4%), followed by rough grazing (11.9%), cereal and other crops (7.7%) (CSO b, 2018).

1.2. Phosphorous losses

Phosphorous has naturally cycled between land and water for millennia in a system known as the P cycle. Over the past 150 years, human activity has substantially impacted and continues to impact this cycle through various processes (Filippelli, 2008). The changes are generally associated with losses of P to the environment, Álvarez et al. *(2018)* highlight five EU secondary P sources or flows, which include municipal wastewater sewage sludge, municipal wastewater treatment plant (WWTP) effluent, organic wastes, and agricultural losses to water and food processing waste. Concerning P losses in municipal wastewater, the development of sewers has changed the natural phosphorus cycle, carrying human waste transported in liquid form to rivers and seas, creating a physical block preventing the P from cycling traditionally by being returned to the land (Ashley et al., 2011). This change has led to a substantial transfer of nutrient loadings from the land to the water, with an estimated 1160 t of dissolved P being released annually to Irish receiving waters by municipal wastewater sources (Mockler et al., 2017). This accounts for up to 42% of the total estimated P pollution contributing sources. The increase in nutrient loads to riverine and receiving water bodies poses a significant threat to the marine ecosystem (Wu et al., 2019).

The reversal of damage to receiving water bodies caused by eutrophication should pursue a systematic approach to integrate hydro systems, agriculture, urban areas and production, and feeding and recycling practices (le Moal et al., 2019). Special emphasis should be placed on recovering and optimizing existing indigenous P sources in the context of nutrient recycling.

1.3. Indigenous sources of phosphorous

In recent years several technologies have been developed to recover P from various municipal and industrial wastewater streams for use as P rich fertilisers, as listed by Ryan et al. (2014). These recovery principles will be examined to identify the quantity of P that can be recovered from municipal WWTP effluent. The quantity and location of municipal wastewater sludge P produced nationally will be quantified, as sewage sludge is a significant potential source of indigenous recycled P with an estimated 70,894 dry tonnes of sewage sludge produced in the Republic of Ireland in 2015 (Water, 2016).

In 2017 Ireland produced 7262.5 million liters of milk, the processing of which produces significant waste streams and will be examined for both effluent discharge and sludge production (CSO c, 2018). Approximately 128,600 t of dairy sludge was produced in 2015, with an expected increase of 50% by 2020 due to the abolition of Irish milk quotas (Fenton et al., 2017), the present dairy sludge production is unknown. However, the national milk production has increased between 2015 and 2019 by 24.8%, an increase of some 1501 million liters, with a resultant increase in dairy processing sludge likely (CSO h, 2020). The same recovery principles will be applied to the dairy effluent as the municipal WWTP effluent to quantify the recoverable P from the processing plants effluent.

The contribution of animal manures to the Irish P balance will be established and quantified. As of 2016, there were 11.1 million poultry, 1.6 million pigs and 7.2 million cattle kept on 137,500 farms nationally (CSO d, 2016). These animals were typically housed for at least a proportion of the year where the wastes are collected, stored, and mechanically spread on the land as nutrient-rich fertilisers.

1.4. Focus of the paper

This paper aims to examine and quantify the scale of Ireland's soil P deficiencies and estimate the annual quantity of P required to raise soil P levels to the recommended agronomic optimum level. The national P requirement will be determined by considering numerous factors, including the regional soil requirement, crop type, crop demand, agronomic limits, stocking rates, and current legislative limits. Once P requirements are established, this paper will review existing sources and locations of indigenous P in a bid to optimise these sources to build national soil P indexes, reviewing the long-term potential to substitute finite mineral P fertilisers. To determine the extent that this requirement can be offset, various indigenous recycled sources of P are investigated, and the P content of these sources estimated.

2. Materials and methods

2.1. Regional analysis

For this research Ireland's P requirements and indigenous supplies is categorised by Nomenclature of Territorial Units for Statistics 3 (NUTS 3) region. The NUTS classification is a hierarchical system adopted by the European Union to categorise economic territories within the EU. The Republic of Ireland is classified as a whole, as a NUTS 1 region, which is subdivided under NUTS 2 into three regions, which include, the Northern and Western, Eastern and Midland, and the Southern Regions (Eurostat, 2018). Under NUTS 3 the Republic of Ireland is further sub-divided into eight regions. For agricultural statistical purposes, the Central Statistics Office (CSO) has amalgamated the Dublin Region with the Mid-East Region, as the Dublin Region contains the capital city and has a relatively small agricultural capacity (CSO b, 2018; CSO e, 2012). The seven agricultural NUTS 3 regions are presented in Fig. 1 and are listed as follows: Border, Midlands, West, Dublin plus Mid-East, Mid-West, South-East and South-West (Eurostat, 2018).

2.2. Yearly mineral P fertilisers - importing and usage

The national sales of mineral P fertilisers are derived from the 2005 to 2015 fertiliser sales figures, compiled in the Teagasc fertiliser use survey (Dillon et al., 2017). The report details that the long-term use of

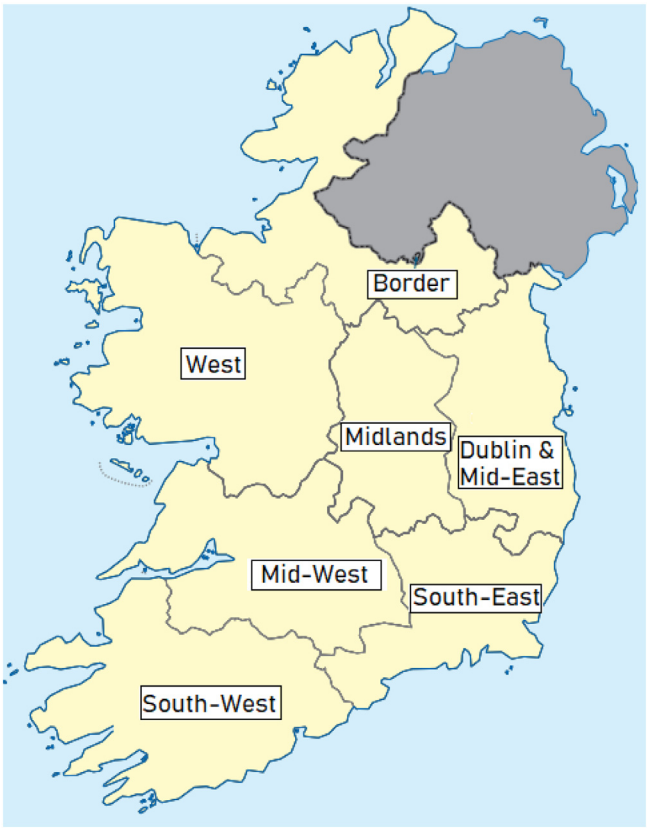

Fig. 1. NUTS 3 regions of Ireland (Eurostat, 2018).

mineral P fertiliser in Irish agriculture was in decline for an extended period until 2009 (Dillon et al., 2017), with the yearly P fertiliser sales declining by 25,225 t, in the period between 1997 and 2010, to 28,775 t (Ruane et al., 2014). Following 2009/2010 P fertiliser sales increased to 36,551 t in 2015 (Dillon et al., 2017). Phosphorous fertiliser sales continued to increase and in 2017 43,000 t of P fertiliser was sold and used in Irish agriculture (CSO f, 2019).

2.3. Regional soil P requirements

2.3.1. Regional land-use

The regional agricultural land usage by NUTS 3 region is derived from the 2017 CSO crops and livestock survey, agricultural area used (AAU) data (CSO b, 2018). For this research, the month of June is used as the benchmark for area cropping data, as it is the midpoint in the growing season, at which time the bulk of annual crops have been planted and established. Rough grazing is excluded from analysis as it is defined by Eurostat as "*permanent grazing with low yield, and normally in poor soils, in mountainous areas, normally not improved by the use of fertilisers, soil mobilisation, sowing or drainage, and which are only suitable for extensive grazing*" (Eurostat, 2019). As the mountainous or undrained bog land terrain does not allow for the mechanical application of organic or inorganic P fertilisers, rough grazing will be excluded from the soil P requirements calculations.

2.3.2. Regional soil phosphorus index

Phosphorus present in the soil is measured as the quantity of plant-available nutrients held in the soil. There are numerous extraction and determination methods; however, Irish legislation has adopted the Morgan's extraction method. The European Union Good Agricultural Practice sets out this method for Protection of Waters Regulations 2017 (S.I. 605 of 2017; ISB, 2017). These regulations provide the main protocol to protect against the negative impacts of agricultural run-off on receiving waters. The regulations stem from Ireland's obligation under Article 4 of the European Council Directive, concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC), to form a nitrates action program.

The regulations also outline the soil extractable P level which classifies a soil's P content into soil indexes 1–4; an index of 1 being the lowest with a P content of between 0.0 and 3.0 mg/L, and an index of 4 being the highest with a soil P content above 8 mg/L. Advice and legislation for applying organic and inorganic P fertilisers are based on soil testing and retaining the soil P index at an optimum level of 3 (ISB, 2017). In 2017 Teagasc, Ireland's national agriculture and Food Development Authority, analysed 45,227 soil samples nationally, with the results published on a county basis (Teagasc, 2017). The soil sample data were categorised by region and used for further analysis of the soil P requirements.

2.4. Sources of indigenous P

2.4.1. Cattle slurry

In 2016 Ireland held an estimated 7.2 million cattle on 109,400 farms, of which 60% were in the Southern and Eastern Regions (CSO d, 2016). For this research, the regional livestock figures were obtained from the CSO 2016 Farm Structure Survey (CSO d, 2016). The keeping of cattle in Ireland is typically based on an external grass-based system with animals only housed (indoors) during the winter period; during the grazing period, animal waste is automatically returned to the soil as organic fertiliser.

During the housing period, farmers are obliged to adequately collect and store animal wastes in designed, sited, maintained and managed holding systems to prevent run-off or seepage of nutrient-rich substances to groundwater or surface waters. The duration and volume of required storage range from 16 to 24 weeks, depending on the location specified by the Standard Instrument 605/2017 European Union (Good Agricultural Practice for Protection of Water) Regulations 2017 (ISB, 2017). Once the specified storage period has concluded, the animal slurry can be returned to the land as organic fertiliser, this research focuses on the P produced during the winter storage period.

2.4.2. Pig slurry

The CSO Crops and Livestock Survey June 2017 highlights that up to 1.5 million pigs were farmed in the Republic of Ireland during the recording period. The keeping of pigs is noted to be conducted on specialised intensive pig farms (CSO b, 2018) leading to the assumption that most Irish pigs are kept under indoor systems, where all feeds are imported and all waste is exported off the immediate pig unit. The CSO Crops and Livestock Survey list the number of breeding pigs per region, the Border Region has the largest quantity of pigs at 39,000 breeding sows and 7000 breeding boars. The South-East has the second-highest quantity of breeding pigs with 38,000 sows and 3000 boars. The West Region has the fewest breeding pigs with 4400 sows and no breeding boars recorded. The production of pig slurry varies depending on the stage of pig growth and the water to meal ratio of the feed. The assessment is simplified to breeding female (sow) place for integrated breeding and fattening units, with one sow and her annual offspring producing 25.1 m^3 of slurry annually of which 17 kg comprises of P, for finishing units solely each pig will produce 2.75 m^3 of slurry annually and 1.7 kg of P (ISB, 2017).

2.4.3. Poultry waste

The regional poultry numbers were published by the CSO Farm Structure Survey 2016 (CSO d, 2016). The regional population figures are presented in the form of laying birds, breeding birds, table birds and other birds. The Border Region has the highest number of both poultry farms and poultry numbers with 7.5 million birds being produced on 1600 farms in the region (CSO d, 2016). The type of poultry

kept on the holding effects the organic manure type and subsequent P content. One thousand egg-laying birds will produce 0.81 m^3 of slurry a week at 30% dry matter, with a total phosphorous content of 2.9 kg per m^3 (ISB, 2017). Table birds are generally produced on a deep litter system using straw or wood shavings to absorb moisture, the resulting manure is measured in tonnes and has a total phosphorous content of 6.0 kg/t (ISB, 2017).

2.4.4. Dairy processing sludge and effluent

A list of approved milk and dairy processing establishments is published by the Department of Agriculture Food and Marine (DAFM, 2020), to comply with the Food and Hygiene Regulations (S.I. 22 of 2020). The list highlights 210 small, medium and large milk processing, packaging and distribution plants. For this research, only large dairy processing plants are reviewed, of which there are 53 facilities. Sludge and effluent data is obtained from each plant's Annual Environment Report (AER) which are published online by the Irish Environmental Protection Agency. Phosphorous production calculations are based on the 2018 set of published AERs as at the time of analysis this data set presented was the most comprehensive set of data. However, of the 53 listed large dairy processing plants, only 20 have published an AER for the highlighted year. Where individual figures from the 2018 AERs were excluded or missing, the data from the 2017 and 2019 AERs were included or interpolated to provide a representative value.

2.4.5. Municipal wastewater sewage sludge and effluent

In 2015 an estimated 70,894 t of sewage sludge was produced in the Republic of Ireland, with the quantity predicted to increase to 84,820 t by 2030. The quantity of regional sewage sludge was obtained from analyzing data presented in the National Wastewater Sludge Management Plan (Water, 2016). Effluent P production was determined from reviewing the wastewater treatment plant AER, which is produced in line with the wastewater discharge licence. A WWTP, with a population equivalent (PE) of over 500 is required to hold a waste discharge licence. While a WWTP with a population equivalent of less than 500 PE is required to hold a waste discharge certificate according to (S.I. 684 of 2007) Wastewater Discharge Regulations (Irish Statute Book, 2007). According to Ryan et al. (2014), there are 520 WWTP locations in the Republic of Ireland holding a wastewater discharge licence, and 556 WWTP locations with a waste discharge certificate. The 2018 annual environment reports are available from the Irish Water website (Irish Water, 2020). There are 108 AER's available on Irish Water's 2018 database, of which three have a design or a load capacity of less than 500 PE. The yearly sludge production and sludge moisture content is presented in the individual WWTP AER. The yearly influent and effluent P emissions to the relevant receiving water body are also recorded.

3. Theory and calculations

3.1. Determination of regional soil P requirements

According to the soil P indexes, the percentage of land within the region can be categorised as a percentage through the analysis of regional land use and the soil index 1–4. Through the determination of the average regional stocking rate, a soil P requirement (kg/ha) by soil index can be determined according to Table 13A of the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017), for grass-based crops. For cereals and other crops, it is assumed that organic animal manures are not applied and hence the regional stocking rate did not apply to these crops.

For the Border Region excluding 148,500 ha of rough grazing, over 595,500 ha of land was farmed in 2017, of which 364,700 was pasture as presented in Fig. 2. In the entire region, 45.3% was categorised at soil index 1, 24.4% at soil index 2, 18.6% and 11.7% at soil index 3 and 4 respectively. The livestock stocking rate for the Border Region was derived from Table 14B of the 2017 National Farm Survey (Dillon et al., 2017), which surveyed 157 farms in the Border Region. The livestock nitrogen stocking rate was determined by multiplying the average livestock units by the yearly nitrogen production per livestock unit, as outlined in the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017; ISB, 2017). The average yearly nitrogen production is divided by the average grazing area to determine the regional livestock stocking rate. It is estimated that the Border Region has a stocking rate of 134 kg of organic nitrogen per hectare per year; it is assumed that no organic manure is applied to arable land.

The P fertiliser application rate for various crops and livestock stocking rates are outlined by the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017). For a nitrogen stocking rate of 134 kg/ha/year, a soil with a P index of 1 is allowed to receive 33 kg P/ha, a soil index of 2 can receive 23 kg P/ha, a soil index of 3 can receive 13 kg P/ha and a soil index of 4 is deemed to be over fertilised and is not allowed to receive P fertilisers.

To determine the regional soil P requirements, the total area of agricultural land per region is multiplied by the percentage of land contained within the region under P index 1. The resultant area is multiplied by the allowable P application of 33 kg/ha. The process is

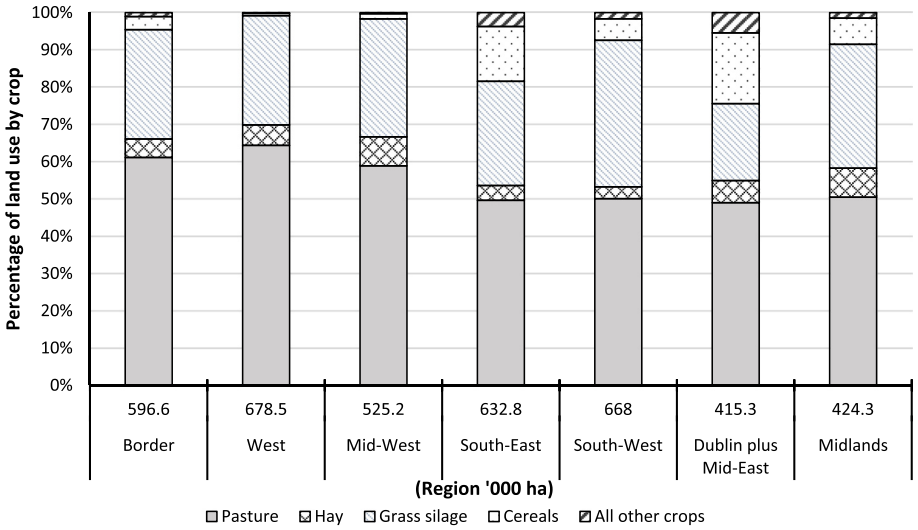

Fig. 2. Irish agricultural land use by region, derived from data obtained from the CSO (CSO b, 2018).

repeated for index 2, 3 and 4, and allows determination of the overall P requirements for pasture in this Border Region. The procedure is repeated for the additional crops, P application for grass silage, hay, and cereals was determined from Tables 15 and 17 of the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017), it is assumed that organic manures are not applied. The P application rate is averaged from the list provided in Table 17 of (S.I. 605 of 2017) for crops other than cereals. This process is repeated for all seven regions within the Republic of Ireland to estimate the national Soil P requirement.

3.2. The determination of indigenous P quantities

3.2.1. Cattle slurry

The annual cattle P production was determined by determining the number of animals and animal types (i.e. 0–1 and 1–2 years old) for each region. The animal type and quantity were multiplied by the annual P excretion rate for the listed livestock type. The annual P excretion rate was derived from the Standard Instrument 605/2017 European Union (Good Agricultural Practice for Protection of Water) Regulations 2017 (ISB, 2017). The regional annual P excretion from cattle was multiplied by the percentage of the year for which slurry storage was required, ranging from 16 to 22 weeks depending on location.

3.2.2. Pig P production

The estimated regional annual pig P production was calculated by multiplying the number of breeding sow places by the estimated quantity of P produced by each pig, as outlined in the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017). Annual pig P production is based on breeding sow place, instead of an individual animal basis, as a breeding sow may have numerous litters of piglets throughout the year, many of which will be reared to slaughter within the same year. It is assumed for calculation purposes that pigs are produced in integrated breeding and fattening units or at a minimum, pigs are bred and fattened within the same region.

3.2.3. Poultry P production

Regional poultry P production was estimated by multiplying bird numbers by yearly bird P production as outlined in the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017). The yearly P production for laying hens and broilers (table birds) is 0.12 and 0.09 kg P per bird place per annum. The P production for other birds is assumed to be that of Turkeys, which produce 0.4 kg P per bird place per annum. The CSO Farm Structure Survey indicates that over 595,000 breeding birds are present in the country. However, it does not specify which category of stock this total represents. Phosphorous production for breeding stock is assumed as the average of table birds, laying birds and turkeys at 0.2 kg P per bird place per annum.

3.2.4. Dairy processing sludge

Previous research on Irish dairy processing sludge and organic residues conducted by Fenton et al. (2017) detailed that an approximate 128,636 t of dairy sludge was produced in 2015, with an expected increase of 50% by 2020, due to the abolition of Irish milk quotas. This predicted increase is challenged by Ashekuzzaman et al. (2019) who estimated, the annual dairy processing sludge production for 2017 at 126,718 tpa, the analysis was conducted by reviewing the 21 available dairy processing plants AER's.

Fenton et al. (2017), tested 16 samples of dairy processing sludge, including dissolved air flotation sludge which had a dry matter (DM) content of 24.5% and P content of 48 kg per tonne of DM and biological treated sludge which had an average DM of 14.55% and average P content of 39.5 kg per tonne of DM. In addition Glanbia Dairy Ingredients Ireland, stated that biologically treated dairy processing sludge, produced at the Ballragget dairy processing plant had a DM content of 15.3% and a calculated P content of 34.6 kg per tonne of dry matter sludge (Trust, 2012). The average dry matter and P content for the three listed sludges was determined at 18.1% DM and 40.86 kg P per tonne of DM.

The dairy sludge production was derived from reviewing the individual dairy processing plants 2018 AERs similar to the analyse conducted by Ashekuzzaman et al. (2019). However, this work accounts for the large dairy processing plants, listed on the Department of Agricultural food and Marines list of approved milk and dairy processing establishments, that don't process a AER. The exact process or origin of sludge presented in the AER was undetermined, for analysis purposes the average characteristics of the sludges highlighted above were taken as representative of national dairy processing sludge. From the available AERs it was determined that on average each dairy processing plant produces 1170.9 t of dry sludge annually, with a subsequent P content of 47.8 t per AER. To estimate the national P production from dairy processing plants, the average P production figure was applied to plants that did not have a published AER.

3.2.5. Dairy processing effluent

The yearly emissions of effluent dissolved P, to receiving waters is presented in the dairy processing plants AER. Dairy wastewater treatment processes vary extensively, depending on the factories manufacturing processing system and scale. There are numerous technologies developed to recover dissolved P, including struvite precipitation. Research has indicated that removal efficiencies of up to 79.3% of PO_4^{-3} from anaerobically treated dairy effluent can be achieved (Uysal and Kuru, 2012). The regional PO_4^{-3} production from dairy effluent was determined and the recovery rate of 79.3% was adopted. Through analyse of the available AERs it was determined that the average dairy processing plant produces up to 0.26 tpa PO_4^{-3} of recoverable P annually, this P production was then applied to the plants which did not have a published AER and converted to present the data as elemental P.

3.2.6. Municipal wastewater sewage sludge

According to Tchobanoglous et al. (2003), the typical phosphorus content of activated sludge is in the range of 1.2–4.7% elemental P of total solids. The regional P production from sewage sludge was determined by analyzing the municipal sewage sludge total solids production per region and multiplying the result by a mid-range sewage sludge P content of 3%.

3.2.7. Municipal wastewater effluent

The majority of Irish WWTP influent P is removed to the sludge, primarily through the standard biological treatment process and some additional P removal steps, with 45% of WWTP listed in the 2018 AER conducting chemical or biological P removal. The remaining dissolved P in the effluent is classed as a liquid phase, according to Cornell and Schaum (2009), between 50 and 60% of P contained in activated sludge treated liquid phase can be recovered. For this research, a mid-range recovery rate of 55% is applied to the regional municipal wastewater effluent P production. The total regional P from municipal wastewater effluent was estimated through interpolation of the AER derived P load.

4. Results and discussion

4.1. Regional land-use

The overall regional land use was analysed, and it was found that various forms of grassland (pasture, hay and silage) were the predominant land use in all regions ranging from 75% in the Dublin plus Mid-East Region to 99% for the West Region. Therefore, the fertilisation strategy for the various types of grassland will significantly impact the P requirement for the regions. The data outlines that the highest levels of cereals are produced in the South-East, Dublin plus Mid-East, and Midlands Regions while high levels of rough grazing were present in the West, South-West and Border Regions. As discussed in Section 2.3.1, rough grazing will not be considered as part of the P

requirement for the region. The agricultural land usage derived from the CSO 2017 Crops and Livestock Survey and presented by NUTS 3 region is shown in Fig. 2.

4.2. Regional soil phosphorus index

Of the 45,227 soil samples analysed by Teagasc in 2017, 16,140 were sampled from dairy farms and an additional 25,729 and 2655 from dry stock and tillage farms respectively (Teagasc, 2017). In total, 26.4%, 20.8% and 16.4% of the national agricultural land are categorised as soil index 2, 3 and 4, respectively. The largest portion of Irish land (36.4%) only achieved soil P index 1. Fig. 3 shows the regional breakdown of soil P index per region. Fig. 3 indicates that on average Irish soil is deficient in P with between 54.9% (Midlands Region) and 69.6% (Border Region) of land categorised as either soil index 1 or 2 (index 1 and 2 means that the land is definitely or likely to respond to the application of P fertiliser). Approximately 12–20% of the land within all regions is deemed to have surplus P content within the soil and is therefore unlikely to respond to the application of P.

4.3. Regional soil P requirements

Based on the soil P index and the land-use of the region, the overall soil P requirement can be determined. The region with the overall highest requirement of P, in absolute terms, is the South East Region with a requirement of 16,700 tpa to maintain crop production and increase soil P levels to agronomic optimum levels. However, when the results are weighted to account for the overall landmass/ha (AAU) excluding rough grazing within the region, the West Region requires the greatest quantity of P per hectare at 44.8 kg/ha. The Dublin plus the Mid-East Region requires the least overall quantity of P with 9756 tpa, while the South-East requires the least quantity of P per hectare at 37.8 kg/ha.

When the regional P requirements are combined, it is estimated that Irish agriculture requires a total of 95,593tpa, to sustain crop production and to build soil P index to the agronomic optimum of index 3 on lands categorised as productive. The national P requirements by region are presented in Fig. 4. Over time as soil P levels increase the national P requirement will decrease. This research has produced a theoretical national P fertiliser requirement, by reviewing regional land use, crop type, animal stocking rates and soil fertility based on the assumption of the P requirement of the crops will be supplied, while raising the national soil P content to agronomic optimum of index 3. This body of work does not review, but acknowledges that raising the national soil P levels will have both positive and negative economic, social, environmental and biodiversity effects.

5. Indigenous recycled P sources

5.1. Cattle slurry

Cattle slurry was the single largest overall indigenous source of P at 19,300 tpa with the South-West Region producing the largest quantity of cattle derived P at 4032 tpa. This is a direct result of the South-West Region having the highest national quantity of dairy cows at 464,700 head and associated imported fertiliser and feed inputs. Dairy cows excrete the largest annual concentration of P per cow compared to other cattle types at 13 kg P per cow per year according to the Good Agricultural Practice for Protection of Waters Regulations 2017 (S.I. 605 of 2017). Dublin plus the Mid-East Region produced the lowest annual quantity of cattle slurry P at 1579 tpa, the annual cattle P production by region is presented in Fig. 5.

5.2. Pigs and poultry P production

The quantity of pig and poultry P available is directly proportional to the number of animals present within the region. Through analysis, it was determined that pigs produced the second largest quantity of indigenous P at an estimated 2400 t P produced per annum nationally. Pig farming in Ireland is concentrated within the Border Region and this is reflected in this region generating the largest quantity of P at 652.3 tpa, this represents 4.2% of the total P requirement for the region, as a whole the border region is comprised of five counties, with varying soil type and farming practices that may affect an individual counties P production/requirement. The lowest quantity of P produced by pigs occurs in the West Region at 74.8 tpa. Poultry was the fifth-largest

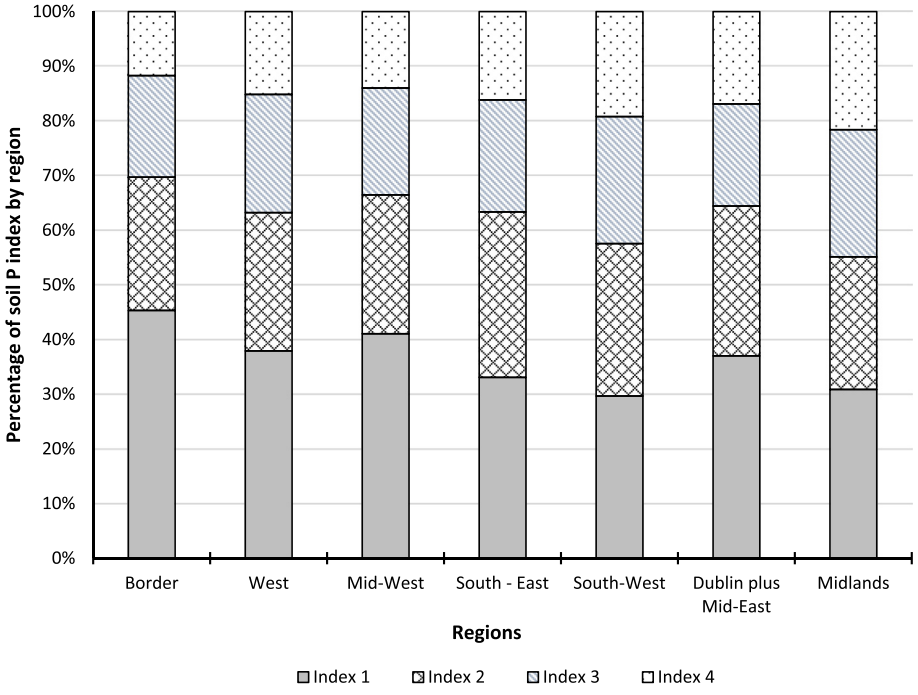

Fig. 3. National soil P indexes by region, derived from data obtained from Teagasc data (Teagasc, 2017).

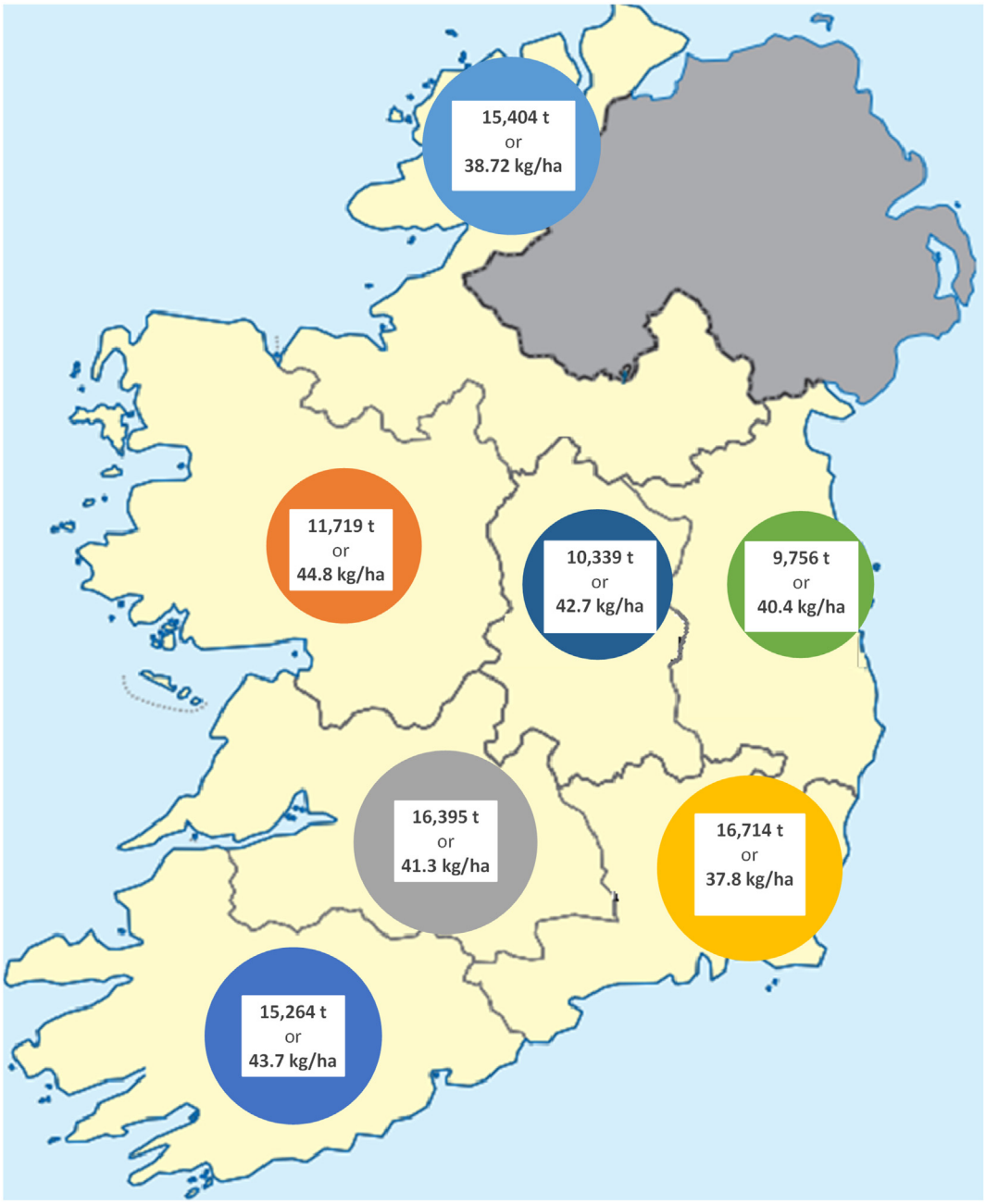

Fig. 4. Regional P requirements in tonnes (t) per region and kg/ha to build soil P index to the agronomic optimum of Index 3 on agricultural area used (AAU) excluding rough grazing.

source of indigenous P nationally at 1300 tpa. Poultry P production followed a similar trend to pigs, with the bulk of poultry production in the Border Region. The Border Region produces an estimated 920.4 t of P per annum which represents 6% of the P requirement for the region. This was followed by the Mid-West region at 108.9 tpa, while the Midlands Region produced the lowest at 14.8 t of poultry P per year. The poultry and pigs regional P production is presented in Fig. 6. In total 3746 tpa can be generated nationally from pig and poultry sources which accounts for 3.91% of the national requirement.

5.3. Dairy processing sludge and effluent

Based on the Department of Agriculture's list of approved dairy processing facilitates and a review of the census located in the southern part of the country 23 of the listed processing plants were located in the South-West region (DAFM, 2020). An estimated 62,057 t of dairy sludge dry matter are produced annually, with an average P content of 40.86 kg/t of dry matter producing an estimated 2535 t of P annually. The largest quantity of dairy sludge P is produced in the South-West Region at 1344 tpa, followed by the Border region which produces the second largest quantity of dairy waste processing sludge P at 385 tpa.

It is estimated that 5.4 t of dissolved P as total P is released into receiving water bodies by the dairy processing industry each year. The South-West Region had the largest production of recoverable effluent P at 2.1tpa. Overall the effluent P production is a small percentage of the overall sludge P production, the national dairy sludge P production is presented in Fig. 7

5.4. Sewage sludge and effluent P

The population of the region directly influences the quantity of sewage sludge and effluent P potential. The largest quantity of P is produced

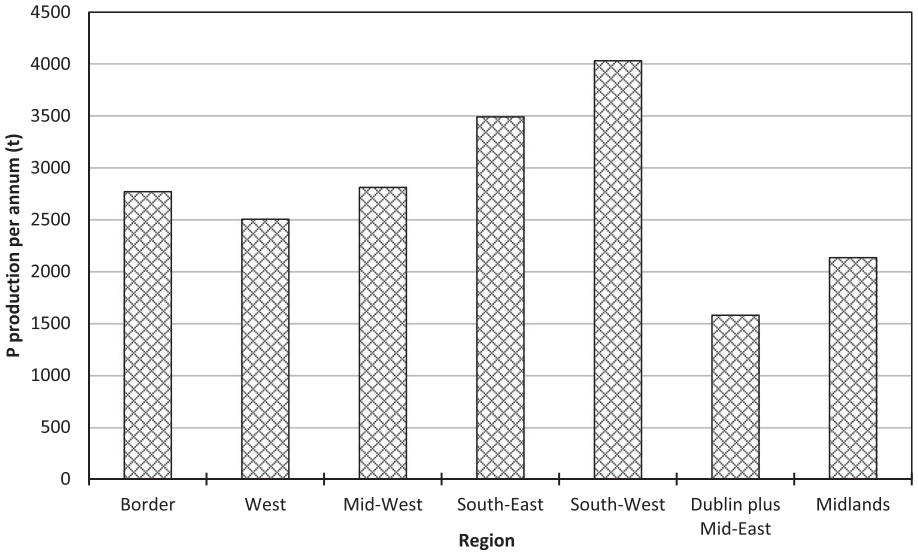

Fig. 5. Regional quantities of recycled P tpa produced by cattle manure.

in the Dublin and Mid-East Region, which contains the capital city Dublin and its commuter belt at 944.5 t (see Fig. 8). The second-largest producer of sewage sludge P was the South-West Region with 303 t. Sewage sludge was the fourth-highest source of indigenous P, with an estimated yearly production of 2127 t of P produced nationally; this equates to 2.2% of the overall national requirement.

By analyzing the wastewater treatment plants' AER and interpolation of results for the 'missing' plants, it was determined that about 1475 t of P enters national receiving water bodies from municipal wastewater treatment plants. Using existing recovery technologies with a recovery efficiency of 55%, a potential 811 t of P could be recovered nationally. The recovery of this P has the added benefit of improving water quality in the region. Again the population of the region directly influences this indigenous source of P, thus the region with the largest potential source is the Dublin plus Mid-East Region at an estimated 284 t of recoverable P.

5.5. Indigenous P summary and soil P deficit

There is a large variation in regional indigenous P sources and quantities, depending on the industry and population within the particular region as shown in Fig. 9 The South-West Region produces the largest quantity of indigenous P with 6470 tpa, of which 62% originates from cattle slurry and 20% from dairy sludge P, the region as a whole produces 42.4% of its annual P requirements.

The Border Region produces the second largest quantity of indigenous P at 5061.5 tpa, of which 54% is derived from cattle slurry, while poultry and pigs, respectively produce an extra 18% and 12.8%. Overall the Border Region produces 32.9% of its P requirements through indigenous sources.

Using indigenous P sources, a total of 28,548 t of recycled indigenous P could potentially be produced in the Republic of Ireland, supplying 30% of the annual P requirement for maintenance and build-up of P to

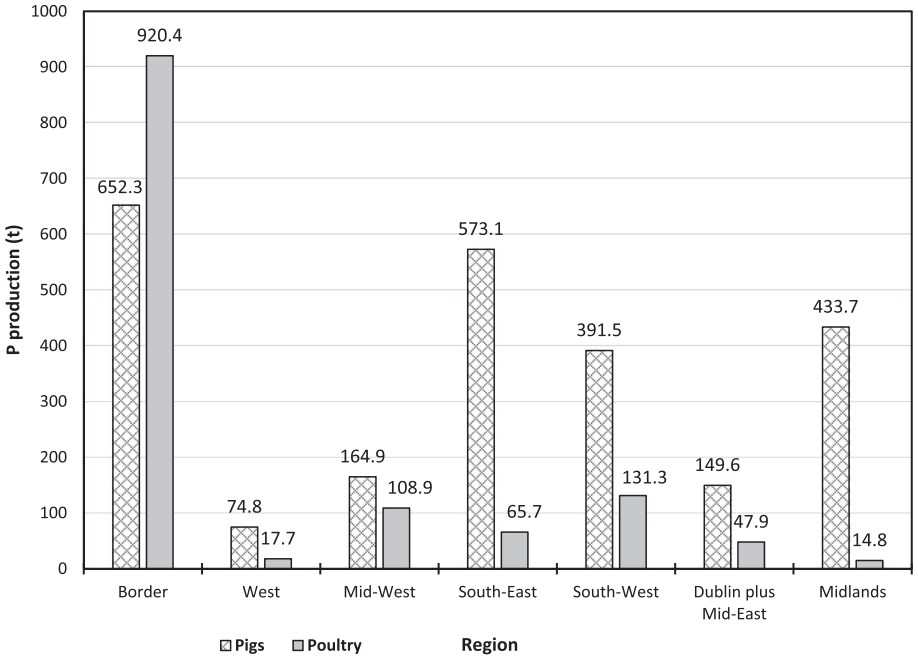

Fig. 6. Recycled P tpa production from pigs and poultry manure by region.

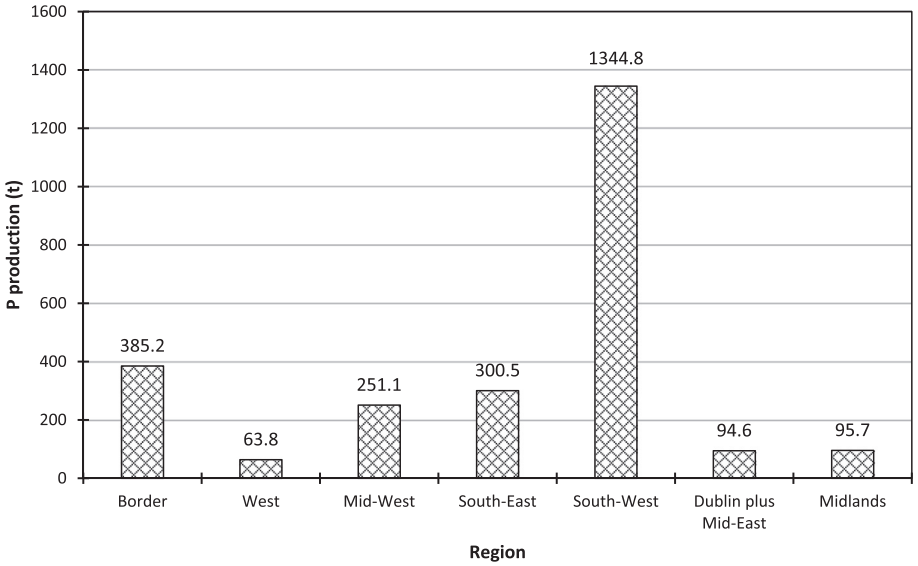

Fig. 7. Dairy processing sludge P production by region.

index 3 on the soils in deficit. This does assume that the recycled P from all sources has the same or similar plant availability as mineral P. The Mid-West Region produced the fifth highest P quantity of indigenous recycled P; however, it has the lowest yearly demand at 22.0%. The regional soil P demand versus regional indigenous P recycling potential is presented in Fig. 10.

The national annual P deficit is found by subtracting the national soil P requirements from the sum of the mineral imported P plus the indigenous P supply. The exercise highlighted a national annual P deficit of 24,044 tpa. This is based on the assumption that all agricultural land throughout the country will be simultaneously farmed to optimum levels and that the socio-economic and farming skillsets are available. The estimate presented also accounts for the quantities of P fertiliser required to raise or build soil P levels to required optimum levels, with up to 63% of Irish soil being classed as having insufficient P. If the outlined quantities of P were to be applied nationally year on year, the national soil P content would gradually increase reducing the deficit and subsequent P requirements over time. Over an extended period of time this would result in the national requirement for imported mineral P fertiliser to decrease, reducing dependence on this source of fertiliser while recovering nutrients that may otherwise be lost to the environment and returning it back to the soil as P rich fertiliser, reducing negative environmental impacts and conserving phosphate rock reserves.

6. Conclusion

The Republic of Ireland has 4.4 million ha of agricultural land; through analysis, it was determined that up to 63% of agricultural land is categorised as having agronomically insufficient levels of plant available P as assessed by the Morgan's soil P test on which national law and agronomic advice is based i.e., soil P index <3. Excluding rough grazing this study reviewed 3.9 million ha of agricultural area used (AAU), accounting for land usage, crop type, animal production and advised P fertiliser application rates, to determine the national soil P requirements from which it was determined that the Republic of Ireland requires an estimated 95,500 t of P fertiliser annually. To sustain crop yields and

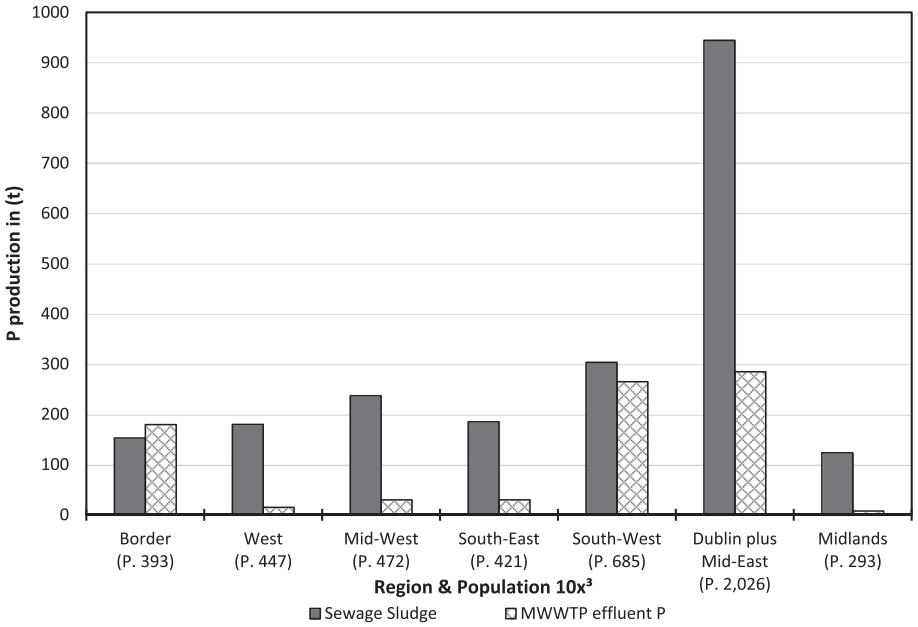

Fig. 8. Municipal wastewater sludge and effluent P production by regional population (CSO g, 2019).

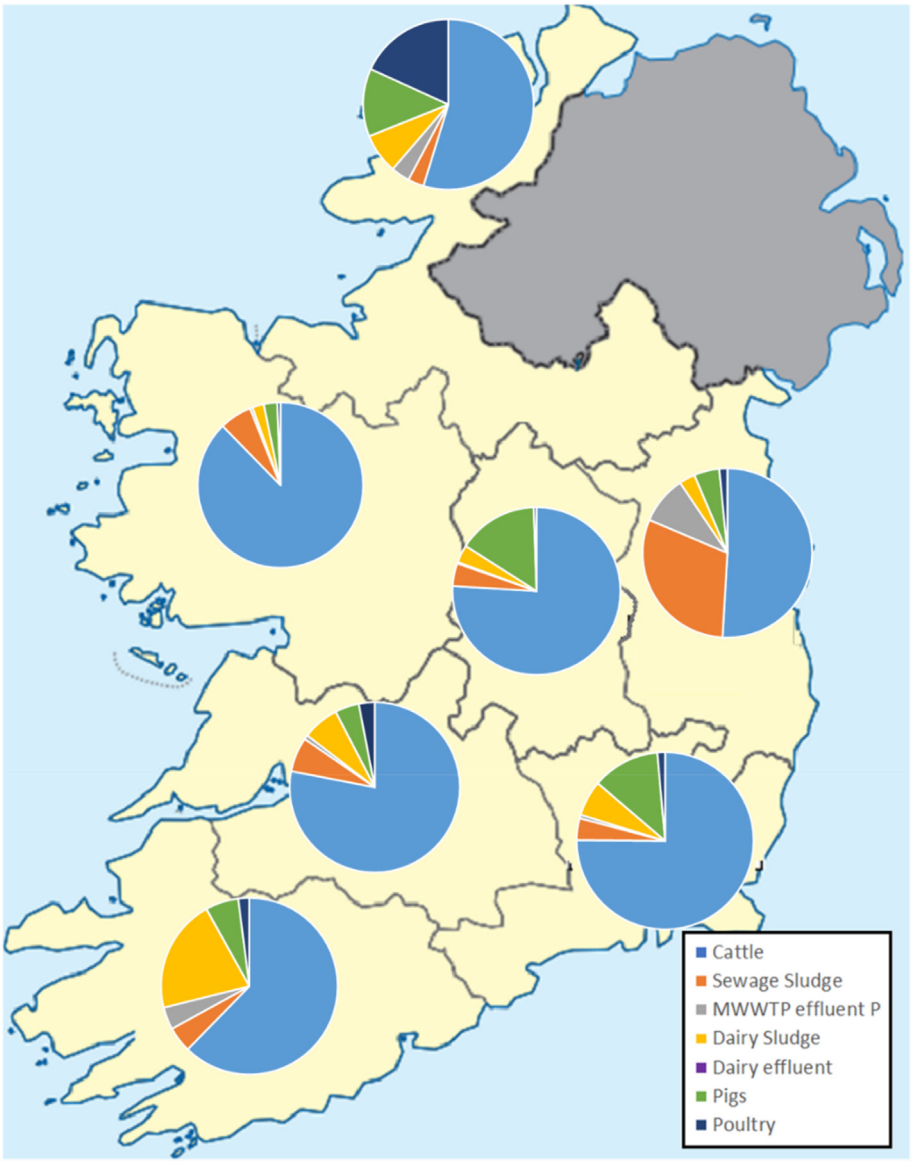

Fig. 9. Indigenous recycled P sources by region.

to build national soil P indexes, of which 63% of grazing and arable land is under optimum soil P levels. To supplement agricultural production, over 43,000 t of finite mineral P fertiliser are imported each year to maintain crop yields.

In a bid to optimise indigenous P recycling and reduce reliance on imported mineral P fertilisers, seven existing P rich waste streams were investigated, including municipal sewage sludge, dairy processing sludge, pig manure, cattle manure, chicken manure, municipal wastewater effluent, and dairy processing effluent. This analysis indicated that up to 1480 t of P are released or lost through effluent from municipal wastewater treatment plants and dairy processing treatment plants to receiving water bodies annually. Using existing P recovery technologies, approximately 816 t can be recovered and reused as a P-rich fertiliser.

In total up to 28,548 t of P can be derived from recycled indigenous sources, of which cattle slurry is the largest indigenous source of P at 19,300 tpa, followed by dairy processing sludge at 2500 tpa. Pig and poultry manure generated an estimated 2400 and 1300 t of P, respectively. Overall the regional indigenous P recycling potential varied greatly by region, depending on the industrial activity and population within the region. The Border Region produced the highest quantity of P derived from animal manures, while the South-West Region produced the highest quantity of dairy processing by-product P. The Dublin and Mid-East Region produced the largest quantity of municipal sewage sludge P. Overall, the percentage of indigenous sources of P that could replace the requirement within a region varies from 22% in the Mid-West to 42% in the South-West Region. Therefore, these indigenous P fertilisers can supply approximately 30% of the national soil P requirement. This research concludes that there is a significant P deficit between national soil P requirements and yearly imported and the potential indigenous recycled P supply. This deficit is estimated to be 24,045 tpa, if optimal soil P levels are to be achieved while sustaining agricultural production.

If additional P was applied to agricultural soil, this deficit would gradually reduce, and so too would the estimated imported P reliance, as soil P indexes increased. It is envisaged that dependency on imported finite mineral P fertiliser could be reduced with time, thus increasing national food and production capacity security. However, soil P levels will require future ongoing maintenance, which can be partly resolved through the effective use of recovered indigenous P fertiliser. The recovery and redistribution of indigenous sources should be prioritized in the development of a vibrant bio-economy.

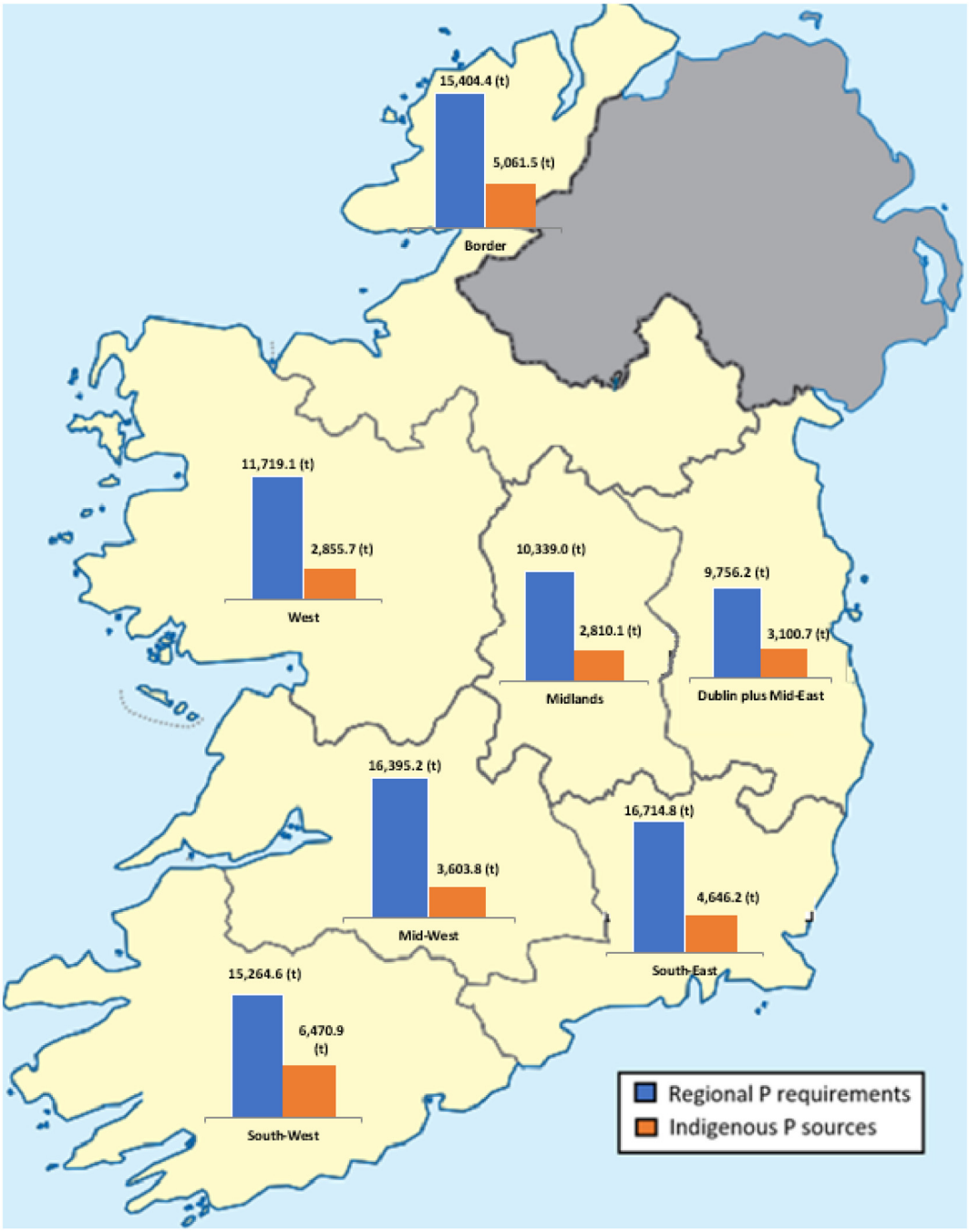

Fig. 10. Combined Indigenous recycled P sources, compared to regional P requirements estimated by P application for maintenance and to achieve optimum agronomical soil P levels.

CRediT authorship contribution statement

Ciarán O'Donnell: Methodology, Investigation, Writing – review & editing. **Aoife Egan:** Writing – review & editing. **Joe Harrington:** Supervision, Writing – review & editing. **Denise Barnett:** Supervision, Writing – review & editing. **Patrick Forrestal:** Writing – review & editing. **Niamh Power:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The EU Interreg North-West Europe (NWE) Program funded this research through the Nutrient Recycling – from pilot production to farms and fields (ReNu2Farm) and the Phosphorus Recovery from Wastewater for Your Life (Phos4you) projects.

Acknowledgements

The authors would like to acknowledge the EU Interreg North-West Europe (NWE) Programme for funding this research through the Nutrient Recycling – from pilot production to farms and fields (ReNu2Farm) and the Phosphorus Recovery from Wastewater for Your Life (Phos4you) projects.

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