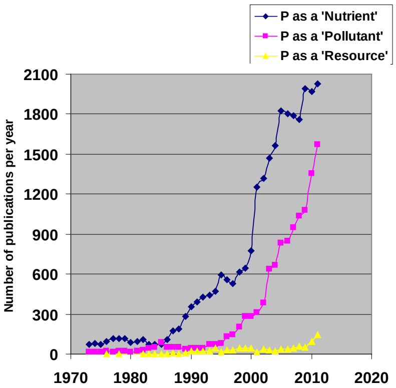
SCOPE NEWSLETTER

European Sustainable Phosphorus Platform

What and why this ESPP SCOPE Newsletter special on phosphorus science?

One of the European Sustainable Phosphorus Platform (ESPP)'s objectives is to be a ***hub for networking, for exchange of information and for interaction between research and industry.*** *This SCOPE special edition aims to identify and summarise some of the most significant, recent, scientific publications into phosphorus stewardship.*



Number of scientific publications per year on Phosphorus (Web of Sciences)

Over the last four decades, the number of scientific articles published on phosphorus sustainability has increased considerably (see graph, Pellerin 2014, in SCOPE Newsletter n°25) reflecting increasing societal and scientific awareness of the importance of phosphorus. Research initially centred on phosphorus' environmental impacts (eutrophication), then more recently on its significance as a critical raw material, essential for agriculture and global food security, and on its potential in the Circular Economy.

This SCOPE Newsletter special summarises a selection of recent science publications *which we think will be of interest to companies, scientists and stakeholders working in nutrient management and concerned by future perspectives for phosphorus. These papers cover different aspects of phosphorus use and stewardship, local or global scales, different themes (recycling, agriculture, food …) and different approaches (technical studies, review papers, societal perspectives, discussion papers). To facilitate access, we have below tried to organise papers by principal theme or approach, but many in fact concern several chapters as they address systemic phosphorus stewardship.*

It has not been possible to include many papers on specialised themes, such as specific technologies or agronomic methods, despite their interest and scientific value. ***The aim is to provide a selection of papers which provide updated general information on phosphorus sustainability, policies and research****, or in some cases new research which although local is of interest to illustrate important new understanding.*

We hope that this overview will be a useful tool to stakeholders engaged in nutrient management, and to researchers, both to provide an overview of trends in scientific understanding and to point to papers you may wish to obtain to deepen knowledge. ***We welcome comments and ideas, and submission of other papers*** *for consideration for review in our newsletters.*

Ludwig Hermann, ESPP President

New books on P- recovery and P-removal

- ***Springer and IWA books review some 30 different P-recovery technologies***
- ***Overview of phosphorus pollution (eutrophication) worldwide***
- ***Update on phosphorus removal in sewage works***

2018 has seen the publication of two books on phosphorus management, sewage phosphorus removal and P-recovery and recycling technologies and policies. Both books include chapters by W. Schipper / C. Kabbe on success factors for P-recycling industrial and market implementation.

The **Springer book, 526 pages**, includes some information on phosphorus flows, Life Cycle Assessment of nutrient recycling and phosphorus rock reserves and processing, but is centred mainly on phosphorus recovery technologies, presenting around 20 technologies for phosphorus recovery from sewage, sewage sludge incineration ash (SSIA), steelmaking slag, manure and bones.

Technologies presented include: Phos4Life Zurich (from SSIA, pilot, see ESPP eNews n°12), Nippon Phosphoric Acid NPA (1300 t/y SSIA processed to phosphoric acid since 2013), alkaline leaching of SSIA (Gifu Japan, 700 t/y SSIA since 2010, see SCOPE Newsletter n°125), Kubota (from sewage sludge, pilot, see SCOPE Newsletter n°126), Ecophos (from ash, industrial scale, see SCOPE Newsletter n°127), Outotec AshDec (from SSIA, industrial pilots), ICL Fertilizers (from ash, industrial testing, see SCOPE Newsletter n°120), Stuttgart (from sewage sludge, pilot), Extraphos Budenheim (from sewage sludge using CO_2, industrial pilot, see SCOPE Newsletter n°103), Hitachi Zosen (Hitz EFCaR Energy Efficient Carbonization, from manure, industrial pilots, pyrolysis producing P-rich biochar fertiliser, see ESPP eNews n°9), HeatPhos (polyphosphate leaching, 2011 pilot see SCOPE Newsletter n°81). Research papers cover high temperature SSIA calcining, CO_2 blowing, struvite and calcium phosphate precipitation, P-recovery from manure, bone char, calcium silicate hydrate and other sorbents, ion exchangers, phosphite oxidation, P-recovery from steelmaking slag (including results of a pilot furnace plant extracting iron-phosphorus alloy – but no indication is given as to the possible use of the resulting material), effects of iron in sewage sludge on P-recovery technologies.

The **IWA book, 590 pages**, provides a wider approach, covering both P-recovery technologies (see below) and phosphorus removal in sewage works (technologies, perspectives, costs …). It aims to take forward to overview initiated by E. Valsami-Jones's (ed.) 2004 book "Phosphorus in Environmental Technologies".

Introductory chapters present overviews of phosphorus resources and eutrophication, including a chapter by A. Farmer (IEEP) providing a global overview of phosphorus environmental issues today. Dr Farmer notes that whilst phosphorus loadings to lakes have been reduced by over a third in Europe and a fifth in Asia 1990 – 2010 they have increased considerably in North America and Africa, and nearly doubled in South America. The status of eutrophication problems in each world continent are presented in detail. Chapters on P-removal in sewage works include overviews of P-concentrations and sources in sewage worldwide and of current biological and chemical P-removal technologies. Chapters address tertiary technologies to remove suspended solids (necessary to achieve low phosphorus discharge consents, see also EWWM in ESPP eNews n°26), effects of P-removal on sludge dewatering, new P-removal and wastewater treatment systems (new biological processes, membranes, microbial fuel cell), costs of different P-removal routes. Phosphorus recovery technologies presented include superparamagnetic particles, electrodialysis, thermal P_4 recovery (ICL RecoPhos/Inducarb (see SCOPE Newsletter n°120), recovery by algae or bacteria, calcium phosphate precipitation, struvite recovery (Ostara Pearl and WASSTRIP, AirPrex, Phospaq, Phosnix), Mephrec slag, Remondis Tetraphos, Parforce, Leachphos, as well as some already indicated in the Springer book above (Extraphos, Stuttgart, AshDec, Kubota) and an overall comparison of technologies (L. Egle et al., see below).

"Phosphorus recovery and recycling", Springer, 2018, Editors H. Ohtake & S. Tsuneda, ISBN 978-981-10-8030-2 https://doi.org/10.1007/978-981-10-8031-9

IWA book "Phosphorus polluter and resource of the future – removal and recovery from wastewater", C. Schaum (ed.), ISBN 9781780408354, https://www.iwapublishing.com/books/9781780408354/phosphorus-polluter-and-resource-future-removal-and-recovery-wastewater

Phosphorus supply, trade and prices

Understanding the phosphorus supply chain

- ***Explanation of the phosphate mining and industry supply chain***
- ***Market and price mechanisms***

Mew, Steiner & Geissler (2018) provide a transdisciplinary 18-page explanation of how the phosphorus supply chain operates, including vocabulary, key questions and policy perspectives. They note that phosphate rock, via mineral P fertilisers, enables around half of current global crop production, but that total "nutrient use efficiency" for P (proportion of mined P ingested in human food) remains very low. The paper explains phosphate ore characteristics, ore contaminants, technologies (exploration for resources, mining, beneficiation, processing to fertilisers and use), economics (in particular, how prices are established in the phosphate rock, phosphoric acid and fertiliser markets), market developments over recent decades and price hikes (1970's, 2008) and policy challenges (including data issues).

"Phosphorus Supply Chain - Scientific, Technical, and Economic Foundations: A Transdisciplinary Orientation", M. Mew, G. Steiner & B. Geissler, Sustainability 2018, 10, 1087, http://dx.doi.org/10.3390/su10041087

Phosphorus price fluctuations and food prices

- ***Phosphate market is unpredictable because a majority of supply is government controlled***
- ***Price volatility***
- ***A doubling of phosphate prices leads to a 3% increase in bread prices***

Mew (2016) explains the links between phosphate rock production costs, world price variability and consequent expected volatility of world food prices. World average phosphate mining operational costs fell by over 1/3 (in real value) from 1983 to 2013, whereas capital costs of opening new phosphate mines increased. However, the market effects of these price changes are not predictable because 2/3 of world phosphate rock production is government controlled. Phosphate prices on the world market are susceptible to considerable price peaks, as occurred in 1975 and 2008. Phosphate rock prices are linked to food prices, with peaks often exacerbated by other energy and resource price peaks. Phosphorus production cannot increase rapidly in response to demand, because of the long mine opening lead-in delay. On the other hand, price increases can lead Western farmers to strongly reduce P fertiliser application, using instead phosphorus accumulated in soils, and so accentuating price slumps after peaks. The paper calculates that a doubling only of phosphate prices can result directly in a 3% increase in the price of bread, whereas the 2008 price peak was an 8 – 10 x price increase. This paper concludes that world phosphate rock reserves are unlikely to be overestimated, and that industry's general position of low concern about resource scarcity is probably justified. New processes are likely to become operational which can use low grade phosphate rock, including previously stockpiled mine tailings. However, most of the world's resources are controlled by Morocco, which may drive phosphorus mining companies in other countries to invest in the future in phosphorus recycling.

"Phosphate rock costs, prices and resources interaction", M. Mew, Science of the Total Environment 542 (2016) 1008–1012 http://dx.doi.org/10.1016/j.scitotenv.2015.08.045 - see SCOPE Newsletter n°122.

Uncertainties in phosphate rock production data

- ***Different data sources for global phosphate rock production show 30% discrepancies***
- ***Official data in some countries may not reflect real market production***

Geissler, Steiner & Mew (2018) analyse differences between data on world (by country) data on phosphate rock production. They note the importance of verifying the units used (metric, long or short tonnes), between capacity and production, and in careful distinction between different materials, in particular between phosphate rock (PR) ore (rock as extracted in the mine) and marketable rock concentrate (PR-M), that is after beneficiation (washing, sizing, flotation). PR-M ranges from below 30% to nearly 40% P_2O_5, that is around 25% higher than ore for sedimentary and around 3 times higher for igneous rock. Data from five sources are compared: IFA (International Fertiliser Association), CRU (consultants, organisers of the annual 'Phosphates' conferences), USGS, BGS (US, British Geological Surveys, BMWFW (World Mining Data / Austrian Ministry of Science, Economy & Research). Discrepancies of up to 30% are found. For 2015 (most recent year with full data available) the Geological Survey estimates of world phosphate rock production are around 20% higher than IFA estimates. The difference is mainly attributable to different figures for China, but also significantly for Peru, probably because the Geological Survey's use official data whereas IFA uses downstream industry information. The authors underline the importance of using accurate data to support public decision making and call for an independent global agency to collect and monitor phosphorus data.

"Clearing the fog on phosphate rock data – Uncertainties, fuzziness, and misunderstandings", B. Geissler, G. Steiner, M. Mew, Science of the Total Environment 642 (2018) 250–263 https://doi.org/10.1016/j.scitotenv.2018.05.381

Changes in phosphate rock quality and mining efficiency

- ***World average grade of phosphate rock increased over recent decades***
- ***But post-beneficiation concentrate grade has fallen***

Steiner et al. analyse developments in phosphate rock mining and beneficiation efficiencies over the last three decades, 1983 – 2013. Average world mined rock phosphorus grade (phosphorus content) increased significantly (+22% from 14.3 to 17.5 %P_2O_5) as did ore tonnage mined (from 513 to 661 million tonnes ore/year). However, changes were not uniform. Mined grades in major sedimentary rock deposits fell (China, USA, Morocco) whereas they improved in some igneous deposits (Brazil, South Africa) but fell in Russia. The average P-rock grade improved in the (large) "other countries" category. At the same time, the phosphorus content of "rock concentrate" (after beneficiation) fell as a world average from 32.5 to 30.1 %P_2O_5, with increases in Morocco and Russia, but decreases in the USA, China and "other countries". The authors see as perspectives a continuing downward trend in rock concentrate phosphorus contents, as mines exploit lower-grade rock and improvements in beneficiation technologies cannot compensate. However, downstream technology changes will make lower grade concentrate acceptable, including both improvements to conventional wet acid processes and new processes able to directly treat low-grade rock. Note: the data presented translate to 51 MtP/y mined annually in phosphate rock and 34 MtP/y in beneficiated rock "concentrate"

"Efficiency developments in phosphate rock mining over the last three decades", G. Steiner, B. Geissler, I. Watson, M. Mew, Resources, Conservation and Recycling 105 (2015) 235–245 http://dx.doi.org/10.1016/j.resconrec.2015.10.004

Understanding the 2008 phosphate price peak

- ***Phosphate price peak was mainly result of India fertiliser subsidy policy dysfunctions***
- ***Other minor contributors: oil prices, weak dollar, China export tax***
- ***Biofuel production not a significant cause***

In 2008, phosphate rock price increased +352% above 2007 prices, before falling back to around +50% higher than 2007 prices by 2014. Fertiliser prices increased in 2008 by +108% DAP (di ammonium phosphate), +140% TSP (triple super phosphate) and +164% potassium chloride. DAP represents over 50% (as P) of world mineral phosphate fertiliser trade. This paper looks at different factors which contributed to these price peaks. The trend fall in value of the US$ made fertiliser cheaper in Brazil, Canada, Russia, India, China, by 13-48% 2003-2008, but is unlikely to have caused the abrupt 2008 spike. A spike in transport costs resulting from increased fuel costs and high demand for freight services is estimated to have doubled average phosphate rock transport costs over 2005-2008, from 25 to 50 US$/t rock. The increase in oil prices (c. +35%) is considered to have made only a marginal contribution to fertiliser prices. The increase in biofuels production, at the global scale, was only +5%, and the total agricultural area was fairly constant (2000-2008, FAO) so this factor is considered not relevant. Market factors, including low fertiliser inventories start 2008 and concentration of market in a few companies and companies, are considered as having likely accentuated the price peak, but with no figures available. Several fertiliser supplying countries introduced export constraints, to protect domestic farmers, accentuating the price peak: global phosphate fertiliser trade fell by -19% in 2008, of which only -7% can be attributed to China (which imposed a 100% export tax on fertilisers).The authors conclude that the biggest cause of the price spike was subsidy policies in India, combined with a reduction in DAP production in India (-25% 2006-2008). The subsidy system led to Indian farmers not adjusting their fertiliser demand to price increases and caused India's imports of DAP to increase considerably, the increase representing around 20% of annual global supply.

"Global Phosphorus Fertilizer Market and National Policies: A Case Study Revisiting the 2008 Price Peak", N. Khabarov & M. Obersteiner, Front. Nutr., June 2017, vol. 4, art. 22
https://doi.org/10.3389/fnut.2017.00022

Agri-food trade leads to phosphorus vulnerabilities

- ***8-fold increase in global phosphorus trade flows in agricultural products over last fifty years (feed, food, crops)***
- ***Of this, nearly half is in animal feeds***
- ***Phosphorus flows in agricultural products represent around 1/3 of mineral fertiliser trade flows***
- ***For the EU, imported phosphorus in agricultural products is over 50% of mineral fertiliser use***
- ***This increase is mainly embedded in trade of animal feeds***

Nesme, Metson and Bennett (2018) assess changes in phosphorus (P) flows in world trade of crops, foodstuffs and animal feeds over the last 50 years. Calculations of P-flows between countries and regions are based on FAO data on agricultural product trade and Food Standards Agency estimates of P-content. P-flows in trade of agricultural products increased eight-fold 1961 to 2011 (reaching 3 million tP/y). By 2011, 20% of P taken up by crops was being exported. 44% of traded P was in animal feeds, 28% in crops and 28% in human foods, and around 2/3 of total flows were in cereals and soybeans. Phosphorus traded in agricultural products is around 27% of that traded in mineral fertilisers. Western Europe (not the whole EU) imported 0.4 million tP/y in agricultural products, that is 16% of global P traded in such products. Significant P flows in agricultural trade originate in the Americas and finish in Western Europe and Asia. The authors note that this global trade of P in agricultural products makes the exporting countries susceptible to the volatility of mineral fertiliser prices.

In an earlier 2016 study, the authors showed that, for the whole EU, total P imports decreased from 0.55 to 0.5 MtP/y from 1995 – 2009. Over this period, EU mineral fertiliser use also fell from 1.9 to 1.1 MtP/y (note this figure is significantly higher than the import figure, because most fertiliser use is for production of crops consumed in the EU). Fertiliser use was also reduced in countries producing the crop products imported into the EU. The part of EU P imports which are "virtual", i.e. in food/crop products not in phosphate rock or fertilisers, increased over the period to 40% in 2009, that is 53% of P use in fertilisers in Europe. Most of the virtual P flow into Europe was from the Americas, plus a small part from South East Asia. Brazil and Argentina represented 27% of these flows in 1995 but more than 60% by 2009. Most of Europe's virtual P imports are in soybean and palm tree products, but also in copra, coffee beans and cottonseed.

"Global phosphorus flows through agricultural trade", T. Nesme, G. Metson, E. Bennett, Global Environmental Change 50(2018) 133-141
https://doi.org/10.1016/j.gloenvcha.2018.04.004

"The surprisingly small but increasing role of international agricultural trade on the European Union's dependence on mineral phosphorus fertiliser", T. Nesme, S. Roques, G. Metson, E. Bennett, Environmental Research Letters, Res. Lett. 11 (2016) 025003
https://doi.org/10.1088/1748-9326/11/2/025003

Phosphorus recycling and processing

Resource recovery and global sanitation implementation

- ***Recycling from sewage worldwide could replace around 5-15% of mineral P fertilisers (N, P and K)***
- ***Biggest potential is from new sanitation installation***
- ***This potential could be increased by 50-80% by installing P-recovery in existing sewage treatment***

Trimme, Cusick and Guest (2017) estimate the potential for global resource recovery from sanitation, and impacts on electricity consumption, in newly installed sanitation, treatment of currently collected but untreated sewage and replacement of existing sanitation systems. Regional and country assessments are also made. Hypotheses (for 2030) of universal global coverage for sanitation and treatment of 50% of currently untreated sewage were modelled, using also UN and FAO projections of population, urbanisation, fertiliser use and food supply. Phosphorus (P) and nitrogen (N) recovery potentials were estimated from diet P and N intakes (nearly all of both elements is excreted) and from different recovery technology options. Water recovery was not considered. Potassium (K) recovery was only considered for source-separated urine. Energy recovery potential was based on excreted carbon. Conclusions are that global recovery potential from new sanitation and water treatment could represent 9-16% of world synthetic fertiliser use for N, 5-15% for P, 10-16% for K and 0-2% of household electricity consumption (this low figure is because most diet energy value is not excreted). 85-86% of this resource recovery potential is from new sanitation. These recovery potentials could be increased by +50-79% by replacing existing sanitation systems with resource recovery technologies. The study also shows that potentials for different resources vary significantly between countries. Because of logistics, resource recovery may be more feasible in rural areas. The study notes that more work is needed on economics, technology costs and financial engineering to enable coverage of higher investment costs for resource recovery by future revenues or savings.

"Amplifying progress toward multiple development goals through resource recovery from sanitation", J. Trimmer, R. Cusick, J. Guest, Environ. Sci. Technol. 2017, 51, 10765−10776
https://doi.org/10.1021/acs.est.7b02147

Potential for improved efficiency in phosphoric acid production

- ***Changing process could significantly reduce P loss in production of phosphoric acid from rock***
- ***This would also reduce water content of phosphogypsum***
- ***Other opportunities include energy efficiency, rare earth metal recovery***

Hermann, Kraus & Hermann (2018) identify and analyse key opportunities for improving efficiency and reducing environmental impacts of phosphate rock processing, summarise key technologies which are today proven. Upstream efficiencies in mining and beneficiation are not discussed. In 2016, c. 83% of mined phosphate rock was used to produce fertilisers, and c. 7% animal feeds. Around 74% of rock was processed by the "wet acid" route (using sulphuric acid to produce phosphoric acid). This generates 4-5 tonnes of phosphogypsum (PG) waste per tonne P_2O_5 in acid, containing contaminants and P, and posing major disposal/stockpile problems. OCP (Morocco) currently discharges PG into the Atlantic, but stated in 2014 the intention to stop this practice. [ESPP editor's comment: disposal to the Atlantic might be considered acceptable, if very well mixed, because this is where the elements in the PG originally came from]. Nearly all (92%) phosphoric acid production uses classical one-crystal processes (dehydrate, hemihydrate) with 5-7% P loss to PG, whereas at least two double-crystal processes are today operational (Prayon DA-HF, Nissan H), reducing losses to 2-3% and also reducing water content of PG from c. 20% to c. 6%. Another key opportunity for improvement is in sulphur combustion (to generate sulphuric acid): the proven Outotec Heros heat recovery system, for example, can improve energy recovery from c. 58% to c. 71%. Other technologies discussed are rare earth metal recovery or radionuclide (uranium) recovery and cadmium removal. The paper also presents Life Cycle Analysis conclusions for mineral phosphate fertilisers, concluding that the two significant environmental impacts are eutrophication (from fertiliser use) and possible cadmium toxicity (input to the food cycle). Life cycle assessment has shown to be an appropriate tool to select process improvements in case of conflicting targets, e.g. removal of heavy metals at the expense of higher energy consumption. Sustainability and efficiency improvements in phosphate rock mining are further discussed in Geissler et al. 2018. Positive illustrations include the OCP Jorf – Lasfar (El Jadida) pipeline, the pilot IHP (Improved Hard Process) and the Yara paste thickener (flotation tailings, Siilinjärvi mine Finland).

"Phosphorus Processing - Potentials for Higher Efficiency", L. Hermann, F. Kraus, R. Hermann, Sustainability 2018, 10, 1482;
https://doi.org/10.3390/su10051482

"Striving toward a circular economy for phosphorus: The role of phosphate rock mining", B. Geissler, L. Hermann, M. Mew, G. Steiner, Mineral Minerals 2018, 8(9), 395
https://doi.org/10.3390/min8090395

Reviews of technical phosphorus recovery routes

- ***Two overviews of technical phosphorus recovery routes (24 processes) based on information available in 2016***
- ***Recovery from sewage sludge incineration ash offers highest % phosphorus recovery***
- ***Costs for P-recovery from ash can be reduced by integration into other processing installations***
- ***LCAs show wide variations between different P-recovery technologies, and important trade-offs***

Egle et al. (2016) and Kabbe (2015), updated in the IWA book chapter (Egle et al. 2018) and the LCA paper (Amann et al. 2018) provide summaries of technological P-recovery from municipal sewage, for processes as documented at the time, summarising technology, economic and environmental aspects. Three P-recovery routes are considered: precipitation from liquid fractions of wastewater, recovery from sewage sludge and recovery from sewage sludge incineration ash. Reuse of sewage biosolids as an organic fertiliser after processing such as composting or digestion are not assessed, but Kabbe et al. note that this route plays an important role in some EU countries (e.g. 65-70% of sewage sludge in France and in the UK) and will remain "one of the pillars for nutrient recycling" worldwide because it is low tech and low cost. These two reviews build on previous publications (e.g. P-REX EU FP7 project http://doi.org/10.5281/zenodo.242550) and on contacts with technology providers and plant visits. In Egle (2016) questions considered include: % P recovery potential, plant availability of recovered nutrient product, contaminant content, texture and handling (farmer use criteria), process cost, savings and revenues resulting from process, technical maturity, uncertainty. Processes assessed are: REM-NUT, AirPrex, Ostara Pearl, STRUVIA, Phospaq, TetraPhos, Budenheim, Loprox, DHV, P-RoC, PRISA, Gifhorn, Stuttgart, Phoxnan, Aqua Reci, Mephrec, AshDec (x2), Pasch, Leachphos, EcoPhos, RecoPhos, fertiliser industry input and thermal P4. Conclusions, based on the process data at the time, are that recovery from sewage sludge incineration ash is promising, with high P recovery % rates. Costs for this route depend on the level of contaminant removal required, and can be optimised if P-recovery is integrated into other existing industrial processes. Kabbe et al. list nearly 50 sites operating technical P-recovery in Europe, with around 20 different technologies. Process summaries are provided for struvite recovery, sludge leaching (Gifhorn, Budenheim) and P-recovery from sewage sludge mono-incineration ash (Ecophos, Mephrec, AshDec, Leachphos). Information on LCA (life cycle assessment), economic, technical and legal aspects are provided. An updated and in-depth LCA assessment of 18 P-recovery technologies is provided in

Amann et al. (2018). Use of sewage sludge (after digestion or composting) in agriculture is not compared. The authors note that for some of the technologies which do not have full scale operating experience process data is unreliable, as are LCA data for some chemical inputs. They conclude that the emissions and energy consumption vary widely between different P-recovery technologies, and that there are important trade-offs between resource recovery rate, heavy metal decontamination, emissions and energy.

"Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies", L. Egle et al., Science of the Total Environment 571 (2016) 522–542 http://dx.doi.org/10.1016/j.scitotenv.2016.07.019

"Review of promising methods for phosphorus recovery and recycling from wastewater", C. Kabbe, C. Remy, F. Kraus, International Fertiliser Society Proceedings 763 (2015) ISBN 1466-1314 http://fertiliser-society.org/Proceedings/US/Prc763.HTM

"Comparison of technologies for phosphorus recovery – identification of an ideal solution", L. Egle et al., in IWA book "Phosphorus polluter and resource of the future – removal and recovery from wastewater", C. Schaum (ed.), ISBN 9781780408354, http://dx.doi.org/10.2166/9781780408361 *Open Access (see above)*

"Environmental impacts of phosphorus recovery from municipal wastewater", A. Amann, O. Zoboli, J. Krampe, H. Rechberger, M. Zessner, L. Egle, Resources, Conservation & Recycling 130 (2018) 127–139 https://doi.org/10.1016/j.resconrec.2017.11.002

Estimated costs of phosphorus recovery

- ***Net P-recovery operating costs estimated at 0-3 € per capita per year***
- ***Value of recovered phosphorus estimated at 0- 1.4€ per capita per year***

Nättorp et al. (2017) publish estimations of overall costs of phosphorus recovery for different phosphorus recovery processes (struvite precipitation: Airprex, Ostara Pearl, Veolia Struvia), sludge leaching (Gifhorn, Stuttgart), metallic slag (Mephrec), ash leaching (LeachPhos, Ecophos), P-recovery from ash (AshDec). This is based on the P-REX FP7 project results (see SCOPE Newsletter n°115). P-recovery is estimated to cost 0 – 3 € per capita, taking into account possible benefits (reductions of operating costs, such as lower maintenance, polymer use or dewatering costs related to struvite recovery in biological phosphorus removal sewage plants). This is without taking into account 0 – 1.40 €/kgP income from sales of recovered product as a fertiliser. One-off investment costs are estimated at 0 – 10 € per capita. For recovery from ash, a further 2 € per capita may be added for installation of "mono-incineration" (incineration of sewage sludge incineration ash separately, not mixed with low phosphorus wastes such as municipal refuse).

"Cost assessment of different routes for phosphorus recovery from wastewater using data from pilot and production plants", A. Nättorp, K. Remmen & C. Remy, Water Sci Technol (2017) 76 (2): 413-424 http://dx.doi.org/10.2166/wst.2017.212

Research needs

Organic phosphorus in soils

- ***Organic phosphorus forms in soils can contribute to phosphorus losses***
- ***Further research is needed into interactions with soil organic carbon stewardship***

George et al. (2017) present conclusions of the 2016 Organic Phosphorus Workshop with 102 participants. An important part of soil P is in organic forms (e.g. monoesters, inositol phosphates, diesters and phosphonates). Once released from humus, they tend to have low affinity to soil particles, and organic P forms can make a large part of P leachates. Research into organic P in soil has accelerated from c. 150 publications in 2000 to around 400 in 2016. Organic soil P is significant as a P source for crops, has ecosystem and biodiversity benefits and interacts with soil carbon storage. Nutrient recycling can increase the return of organic P to soils. Research needs identified are: soil organic P models, analysis methodologies, understanding stoichiometry – interactions with cycles of other elements, interactions with land management, interactions with natural and man-made nanoparticles, better communication of research.

"Organic phosphorus in the terrestrial environment: a perspective on the state of the art and future priorities", T. George et al., Plant Soil June 2018, Volume 427, Issue 1–2, pp 191–208 https://doi.org/10.1007/s11104-017-3391-x

Research needs for agriculture with lower phosphorus losses

- ***25 research needs to address agricultural phosphorus stewardship were identified at IPW7***
- ***These are presented in summary table and 16 page detail***
- ***Importance of co-benefits with water and biodiversity management***

Sharpley et al. (2015) summarise conclusions of the 7th International Phosphorus Workshop (IPW7), Uppsala, Sweden, at which 150 participants discussed P management, soil – water P pathways, monitoring and modelling, manure and P loss mitigation. To address these challenges, 25 research needs were identified. These include crop breeding for P efficiency, site specific fertilisation optimisation, models and monitoring, changing land use and restructuring of agricultural production systems, manure treatment which improves fertiliser value, public acceptance of recycled nutrients, processes to sequester P in soils or biowastes whilst leaving it plant available, defining realistic surface water restoration objectives and strategies. These research needs are listed in a one page table and justified in detail over 16 pages. Conclusions emphasise the difficulties of scaling (be it application of overall policies at the local level, or interpretation of field results to generalised models) and the co-benefits which can result from management actions (e.g. renaturation of watercourses to delay P transfer and increase retention can benefit hydrology and biodiversity).

"Future agriculture with minimized phosphorus losses to waters: Research needs and direction", A. Sharpley et al., AMBIO 2015, 44(Suppl. 2):S163–S179 http://dx.doi.org/10.1007/s13280-014-0612-x

Research into phosphorus in agriculture and ecosystems

- ***IPW8 concludes need for wide agricultural policies to address phosphorus***
- ***Need for regulatory framework for placing recycled nutrient products on the market***
- ***Importance of price and economic instruments***

Leinweber et al. (2018) summarise conclusions of the 8th International Phosphorus Workshop (IPW8), Rostock, Germany, 2016,from which papers are published as a special issue of AMBIO (see ESPP eNews n°22), looking at P flows, recycling routes and governance. On recycling, conclusions are that regulatory action is needed to support P-recovery and enable placing on the market of recycled fertilisers, links need to be made with recovery of other nutrients, and up- and downstream value chains better addressed: P-containing waste should be avoided upstream, or generated in forms that support P-recovery, and recovery should be designed to generate products with a viable market as fertilisers or in industry. On agricultural P management, further research is needed into catchment dynamics, impacts of P-loss mitigation measures, innovative mitigation actions including controlling drainage and long-term impacts of conservation practices on both particulate and soluble P losses. Regarding governance, the authors note the risk of failures of P reduction policies because of ineffective enforcement, transfer of P pollution generating activities to other regions or rebound effects of increased land use, and call for wide policies such as reducing agricultural subsidies, including livestock emissions in greenhouse emission trading schemes, price/tax on agricultural land use an primary nutrient use, as well as classical environmental and technical regulatory instruments.

"Handling the phosphorus paradox in agriculture and natural ecosystems: Scarcity, necessity, and burden of P", P. Leinweber et al., Ambio 2018, 47(Suppl. 1):S3–S19 http://dx.doi.org/10.1007/s13280-017-0968-9

Note that IPW9 will take place in Zurich, 8-12 July 2019
http://www.plantnutrition.ethz.ch/ipw9.html

Final report EIP-AGRI Focus Group on Nutrient Recycling

The European Commission EIP-AGRI "Focus Group" on Nutrient Recycling has published in November its final report and eight of mini-papers. The conclusions were summarised in detail in SCOPE Newsletter n°124, February 2017. The final report makes recommendations to EU research and RDF rural development policies (Operational Groups). Seven research needs identified are: LCA, Nutrient Use Efficiency assessment methods, organic contaminants (impacts, mitigation), perception and acceptance of recycled nutrients, remote sensing to support precision fertilisation using bio-based fertilisers, on-farm techniques for nutrient recovery and for measuring nutrient content in manures, production of recycled nutrient products adapted to specific crops and with reliably consistent composition. Recommendations for Operational Groups are: demonstration of nutrient recycling and of use of recycled nutrient products, integration of recycled nutrients into food-industry quality and certification schemes, cooperative business models for nutrient recycling and exchange of experience between farmers of bio-based fertilisers.

European Commission, EIP-AGRI Focus Group "Nutrient recycling. How to improve the agronomic use of recycled nutrients (N and P) from livestock manure and other organic sources?", final report and mini-papers https://ec.europa.eu/eip/agriculture/en/focus-groups/nutrient-recycling Summary in SCOPE Newsletter n°124.

US Phosphorus Research Coordination Network conclusions

- ***Key questions: Legacy P, Soil P, P efficiency***
- ***Need for Agricultural BEMP Fact Sheets***
- ***Need for long term field trials***

The US P-RCN (2013-2017, Phosphorus Sustainability Research Coordination Network brought together around 40 scientists from the US and the rest of the world. Its final meeting conclusions are presented in SCOPE Newsletter n°125. The Network particularly addressed: legacy phosphorus, phosphorus removal and recycling technologies, metrics and data, the nutrient – water – energy nexus, Transition Management Pathways (action on phosphorus address food security, resource dependency and environmental impacts). Key outstanding questions were identified as: where is legacy phosphorus present in soil, and what are its impacts? How to measure soil phosphorus? What is meant by "Phosphorus Efficiency" (efficiency of use in crops, between mine and plate …) ? Other research questions identified are: Ecosystem services and costs, Catchment modelling, Need for long term field trials, Need to update published agricultural BEMP (Best Environmental Management Practice) Fact Sheets.

US P-RCN (2013-2017, Phosphorus Sustainability Research Coordination Network (US National Science Foundation) conclusions SCOPE Newsletter n°125 www.phosphorusplatform.eu/Scope125 and https://phosphorusalliance.org/

Phosphorus flows, footprints and use scenarios

Overview of world phosphorus flows and challenges

- ***Overview of global phosphorus flows***
- ***1/5 of mined phosphorus reaches food we eat***

Cordell and White (2014) update Cordell's ground-breaking paper of 2009 on phosphorus stewardship challenges. Key data on global phosphorus extraction, uses and losses is summarised in a one page diagram (p164). Overall, around 20% of phosphorus mined is estimated to reach food consumed. 12 MtP/y is estimated to be accumulating in agricultural soils. The paper summarises aspects of phosphorus "scarcity": physical (resources and reserves), management of resources, economic inaccessibility (1/6 of the world's farmers cannot afford adequate phosphate fertiliser), geopolitical (distribution of reserves) and institutional (lack of global governance). Trends, scenarios and strategies for phosphorus stewardship, based on food security and ecosystem integrity, are considered.

"Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future", D. Cordell & S. White, Annu. Rev. Environ. Resour.

2014. 39:161–88 http://dx.doi.org/10.1146/annurev-environ-010213-113300

"The story of phosphorus: Global food security and food for thought", D. Cordell et al., Global Environmental Change, vol.19, Issue 2, May 2009, pages 292-305 http://dx.doi.org/10.1016/j.gloenvcha.2008.10.009 updated in

Nutrient management scenarios for Austria

- ***Development of combined nitrogen and phosphorus MFA and management scenarios***
- ***National phosphorus management scenarios based on MFA (material flow analysis)***
- ***Healthy diet, improved use efficiency and recycling could nearly eliminate dependency on imported phosphorus***
- ***Biggest opportunities are diet change (less meat), animal feed efficiency, sewage P recycling, meat and bone meal***

In Zoboli (2016), based on a detailed phosphorus flow analysis (MFA) for 2013, policy priorities for phosphorus management in Austria are defined. A combination of reduced phosphorus consumption and phosphorus recycling would divide dependency on imported phosphorus by ten (from 2.2 to 0.23 kgP/capita/y), reduce losses to surface waters by nearly 30% and eliminate the need for fossil phosphorus fertiliser consumption. Reduced diet-based P consumption potential (3 700 tP/y) is based on Thaler (2015) who showed that moving to German Nutrition Society and WHO recommendations would reduce meat and dairy intake by 60%, so reducing P consumption in agriculture because of the low efficiency in animal production. The study also estimates possible P consumption reductions through increased crop farming P efficiency (1 500 tP/y), optimisation of P content in animal feed 3 700 tP/y). Phosphorus recycling potentials include meat and bone meal (3 240 tP/y), sewage sludge (currently only around ¼ is used in agriculture, the rest goes to landfilling or landscaping) (4 200 tP/y) and others (composts, biomass ashes, organic wastes), reduction of surplus accumulation in soils in private and public gardens and parks (2 000 tP/y) and reduction of erosion losses from agricultural soils (2 200 tP/y). Tanzer et al. (2018) take this further by combining analysis of phosphorus and nitrogen flows and policy scenarios. This shows that there may be trade-offs, such as possible increased nitrogen losses to air if organic materials are recycled to agriculture replacing mineral fertilisers. Much the largest optimisation potentials identified for nitrogen, for reducing mineral fertiliser demand and for reducing losses to air and water are fertiliser use efficiency and dietary changes.

"Supporting phosphorus management in Austria: Potential, priorities and limitations", O. Zoboli, M. Zessner, H. Rechberger, Science of the Total Environment 565 (2016) 313–323 http://dx.doi.org/10.1016/j.scitotenv.2016.04.171

"Filling two needs with one deed: Potentials to simultaneously improve phosphorus and nitrogen management in Austria as an example for coupled resource management systems", J. Tanzer, O. Zoboli, M. Zessner, H. Rechberger, Science of The Total Environment 640–641, (2018) 894-907 https://doi.org/10.1016/j.scitotenv.2018.05.177

Increasing phosphorus use and impacts in China

- ***Phosphorus contained in crops and livestock increased by 2-4x over recent centuries in China***
- ***N and P losses to surface waters increased by 4x***
- ***P input to China's cropland is >2x higher than crop uptake***
- ***Only around 4% of P used was finally ingested in food***

Liu et al. (2016) assess P cycles in China over the last four centuries. Phosphorus tonnages in harvested crops and animals increased by factors of 2x and 4x respectively from 1600 to 1900, despite decreases in some periods of lower agricultural production. Since the early 1900's, with development of domestic phosphate rock and fertiliser production, P in crops increased rapidly (0.8 in crops in 1900 to 3.3 mtP/y in 2012). By 2012, P input to cropland was 7.5 mtP/y in fertilisers, plus 1.5 mtP/y in manure, with average P application of 80 kgP/ha, more than twice the inputs most crops can take up. Overall, around 4% of P used was finally ingested in food (slightly lower than 5% for the USA: Suh 2011). At the same time, the level of P in diets did not change significantly from 1950 to 2012, the proportion of P from plant products fell from 98% to 76%. Phosphorus losses to freshwaters tripled over the past four centuries reaching 1.6 mtP/y in 2012, compared to revised estimates of atmospheric deposition of 1.5 mtP/y (60% from combustion). Only around 1/5 of P lost to rivers in China is estimated to reach the open sea, the rest being retained in river and coastal sediments (because of relatively flat terrains and artificial dams).South East China is identified as particularly suffering intensive eutrophication damage. The authors note that the China State Council announced in 2015 the objective to reduce environmental impacts of agriculture including by capping fertiliser use by 2020.

"Intensification of phosphorus cycling in China since the 1600s", X. Liu et al., PNAS March 8, 2016, 113 (10) 2609-2614 https://doi.org/10.1073/pnas.1519554113

Also cited: Phosphorus use-efficiency of agriculture and food system in the US, S. Suh et al., Chemosphere 84 (2011) 806–813 https://doi.org/10.1016/j.chemosphere.2011.01.051

Urban sewage phosphorus flow case studies

- ***Rates of urban P recycling vary considerably, depending on sewage collection and biosolids use***
- ***Logistics and public perception are important factors, in addition to regulation and funding***

Metson et al. 2017 assess P flows in urban sanitation in Accra (Ghana), Buenos Aires (Argentina), Beijing (China), Baltimore (USA) and London (UK), in order to establish what proportion of P from human excreta is returned to agriculture and consider what socio-economic factors impact this. Other urban P flows, such as food waste, pet excrement, food processing or industry are not considered. London has the highest rate of return of P to agriculture or other productive uses, at 89% (64% to agriculture and 25% to landscaping, forestry, etc.) because of high levels of sewage collection and treatment including P-removal, and use of sewage biosolids (generally after anaerobic digestion) in farming. For Baltimore over half of collected sewage is treated outside the state, and the recycling rate is unknown. In Beijing over half of sewage P is 'lost' to landfill. The proportion of P from sewage lost to surface water depends on sewage collection and treatment, and varies from 84% in Accra to 11% in London. The authors conclude that factors such as regulation and access to capital resources for sanitation investments are necessary conditions to achieve sewage P-recycling, but may not be sufficient, with transport and logistics, and social perceptions of sewage nutrients also being important.

"Socio-environmental consideration of phosphorus flows in the urban sanitation chain of contrasting cities", G. Metson, S. Powers et al., Regional Environmental Change (2017) https://doi.org/10.1007/s10113-017-1257-7

Policies, phosphorus flows & crop efficiencies in Switzerland

- ***P reuse fell from c.70% to <10% in Switzerland as a consequence of the ban on sewage biosolids land use and restrictions on reuse of animal by-products***
- ***NOTE: this will be reversed with the new Swiss P-recycling ordinance***
- ***From 1990 to 2015 soil P accumulation was reduced over 40x***

Mehr, Jedelhauser & Binder (2018) assess changes in P flows and plant production efficiencies in Switzerland 1989 – 2015 and analyse impacts of public policies. Based on national-level SFA (substance flow analysis) for Switzerland, they derive three indicators: TID = total import dependency, PEP = P efficiency in plant production and PLW = P losses in waste management. In 2015, Switzerland was a net P importer (10 000 tP/y = c. 3.4 gP/person/day) mainly in animal fodder, mineral fertiliser and foodstuffs. In 2015, only around 10% of P in wastes and wastewaters is recycled in Switzerland (manure and on-farm crop materials not included). Recycling fell -70% from 1989 to 2015 as a result of policies preventing agricultural use of sewage biosolids and animal by-products. On the other hand, crop P efficiency (PEP) improved from 59% to 94%, and in particular soil P accumulation was reduced from nearly 17 kgP/ha in 1989 to 0.4 kgP/ha in 2015. This was due to the 1993 Ordinance on "Integrated Production" which required (from 1999) balanced N and P budgets as a condition for farm subsidies (Proof of Ecological Performance ÖLN), but probably also due to the ending of sewage biosolids application, higher fertiliser prices and past over-fertilisation. P losses to surface water from sewage works were reduced from 2000 tP/y in 1989 to 900 tP/y in 2015, but diffuse inputs from agriculture contributed a further 1100 tP/y. Data gaps identified include P flows in industrial applications and in certain animal by-products as well as concentrations in municipal solid waste.

"Transition of the Swiss Phosphorus System towards a Circular Economy - Part 1: Current State and Historical Developments", J. Mehr, M. Jedelhauser, C. Binder, Sustainability 2018, 10, 1479, https://doi.org/10.3390/su10051479

How much could phosphorus use be reduced?

- ***Dietary change and recycling could reduce Europe's mineral P input need by up to 90%***
- ***This assumes complete crop waste, slaughterhouse and sewage phosphorus recycling***

A theoretical optimisation model of agriculture, human diet, phosphorus use and recycling suggests that mineral phosphorus input could be reduced by 90%, assuming complete recycling of crop wastes, slaughterhouse waste phosphorus, animal manures and human excreta, no soil P accumulation and low soil P losses (compared to a "baseline" situation based on current Netherlands data, with 60% of diet protein from animal sources, less than 50% of crop waste recycling and zero recycling of slaughterhouse waste and sewage phosphorus). If phosphorus were fully recycled (including crop wastes, sewage, slaughterhouse wastes) a small amount of animal protein in the diet (around 10%) would result in the lowest mineral phosphorus consumption. In scenarios without full recycling of slaughterhouse waste, a vegan diet led to the lowest mineral phosphorus need. The lowest mineral phosphorus need per year is estimated at over 1 000 tonnes(P)/year for a population of 17 million people. ESPP NOTE: this would be 0.45 million tonnes P/year world mineral fertiliser use (7.7 billion population), compared to 16.5 - 22 MtP/y world fertiliser use (figures in Cordell 2014 and Hermann et al. 2018 above), with the assumptions above (e.g. no soil P accumulation).

"Closing the phosphorus cycle in a food system: insights from a modelling exercise", H. van Kernebeek, S. Oosting, M. van Ittersum, R. Ripoll-Bosch, I. de Boer, Animal, Volume 12, Issue 8, August 2018 , pp. 1755-1765 https://doi.org/10.1017/S1751731118001039

Discussion papers

Overview of sustainable phosphorus use in society

- ***c. 30 MtP/y are mined compared to anthropogenic need of c. 1MtP/y***
- ***Policies are discussed for stewardship, efficiency, lowering demand, recycling***

Withers et al. (2015) provide an overview of industrial and food system phosphorus uses and discuss general policy options to encourage more sustainable phosphorus management based on closing the phosphorus cycle, and adoption of the principles and practices of green chemistry and the circular P economy (use minimum inputs, develop benign systems that run on renewable materials and design out waste). They note that around 30 million tP/y (phosphorus) are mined in phosphate rock, whereas real anthropogenic requirement is only around 1 mtP/y, showing the inefficiency of current phosphorus cycles and the magnitude of the challenge. They discuss losses occurring in particular in mining, P accumulation in soils and agricultural losses to water as well as losses in slaughter house wastes and sewage treatment. They suggest that green chemistry and green engineering can be applied to help close the global P cycle by addressing three sustainability challenges: (1) consume less phosphate rock and with greater efficiency, (2) minimise P losses and generation of waste P that can no longer be re-used, and (3) set economically, socially and environmentally acceptable P sustainability targets to lower P demand. Technical challenges to reducing losses include recovery of phosphorus from low-grade ores, manure processing, phosphorus recovery in food processing industries, wastewater P-recovery and production of white phosphorus from waste materials. Suggested actions in the agri-food sector include lowering P demand, improving phosphorus use efficiency and fertiliser design, adjusting animal feeds and dietary choices.

Greening the global phosphorus cycle: how green chemistry can help achieve planetary P sustainability, P. Withers et al., Green Chem., 2015, 17, 2087 https://doi.org/10.1039/c4gc02445a

Co-benefits of phosphorus recycling

- ***Co-benefits of P-recycling include return of organics to soil, bio-energy, water quality and societal benefits***

Mayer et al. (2016) present discussions on the different benefits of recovering or recycling P from waste streams. The different values additional to the value of the P itself are indicated, without quantification. Where P is recycled in organic forms (e.g. agricultural application of sewage biosolids, composts, etc.) cited benefits include improving soil water retention resulting from the return of organic carbon to soil, as well as filtering pollutants and supplying trace elements. Processing of such organic wastes can provide renewable energy (methane, hydrogen). Nitrogen, potassium, and other minerals can be recovered in P-recovery processes, as well as water for reuse. Phosphorus recovery has other benefits, including reducing P losses so protecting waters from eutrophication, improving sewage treatment performance. Phosphorus recycling can contribute to improving global food security and social equity. Needs identified to make total value recovery happen are technology improvement, new business models, systems level assessment tools, regulations or incentives, education and public acceptance.

"Total Value of Phosphorus Recovery", B. Mayer et al., Environ. Sci. Technol. 2016, 50, 6606−6620 https://doi.org/10.1021/acs.est.6b01239 *This paper is a US P-RCN outcome (SCOPE Newsletter n°125).*

Phosphorus ecosystem services conceptual model

- ***Research is needed into economic co-benefits of P stewardship and research priorities are proposed***

MacDonald et al. (2016) propose a conceptual framework for phosphorus ecosystem processes, functions and services, called PESC "phosphorus ecosystem services cascade". This links P stewardship policies, P use practices, co-benefits, behaviour of P in water systems and soils, and impacts such as water quality and property and tourism values. These are not yet quantified and the authors call for empirical research to test the model. The authors note the challenges of disconnects (distance, e.g. where consumed P is traded across the world, with use impacts occurring on different continents; time: lag between eutrophication restoration actions and ecosystem recovery) and of accentuating pressures such as climate change. Six research priorities are identified: cumulative downstream impacts of plant-soil P stewardship, multiple ecosystem services in agri-environmental P indices, benefits of increased organic P recycling, catchment-specific P targets for water quality, P stewardship impacts on the water cycle, impacts on P use and management of climate change.

"Guiding phosphorus stewardship for multiple ecosystem services", G. MacDonald et al., Ecosystem Health and Sustainability 2(12):e01251 https://doi.org/10.1002/ehs2.1251 *This paper is a US P-RCN outcome (SCOPE Newsletter n°125).*

Tools and indicators

- ***Stakeholder dialogue tool with scenarios and indicators of phosphorus vulnerability***

Cordell and White (2015) propose a set of 28 "phosphorus indicators" (or metrics), designed for use to assess P vulnerability in food systems at the global or national levels. This is based on previous papers by Cordell et al. on P security (see SCOPE Newsletter n°95) and on analysis of 12 existing indicators on food security, water, environment, sustainable development (e.g. FAO, UN, World Bank …). The proposed indicators address 8 themes relative to phosphorus: price, market and supply risk, scarcity, eutrophication, farmer vulnerability, national vulnerability, equity and soil legacy P. They are intended to facilitate definition of where policy interventions may be required, to enable tracking of changes in P vulnerability and P sustainability performance and to identify research and data gaps. Neset, Cordell et al. (2016) present a web-based global phosphorus scenario tool, intended to enable stakeholders to model different scenarios for meeting P demand for the horizon 2040-2070. The user enters 20+ different variables, expressed as % of 2007 levels, including for example: e.g. world population, crop and livestock P efficiency for different land use types, global proportion of sewage P recycled, per capita food waste. Four example scenarios are presented: full recovery of sewage P, increasing P use in non-food (industrial applications, fertilisers for energy crops …), decreasing animal products in diet, increasing yield and P efficiency in crops and livestock. The objective is to provide a platform tool to support stakeholder dialogue.

"Tracking phosphorus security: indicators of phosphorus vulnerability in the global food system", D. Cordell & S. White, Food Security, 2015, 7 (2), pp. 337 - 350 https://doi.org/10.1007/s12571-015-0442-0

"Visualizing Alternative Phosphorus Scenarios for Future Food Security", T-S. Neset et al., Front. Nutr. 3:47 (2016) https://doi.org/10.3389/fnut.2016.00047

Proposals for global phosphorus governance

- ***Need for international data transparency on phosphate rock production, processing, P-flows, recycling***
- ***Proposal for UN-led action plan***

Rosemarin & Ekane summarise international phosphorus governance needs and gaps and make a proposal for action. These are not validated by stakeholder consultation, nor by science meta-analysis. Theoretical models of Multi Level Governance (MLG) are mentioned (Hooghe & Marks 2001) and a short section mentions organisations contributing to international data transparency or social responsibility for other minerals: World Gold Council, UN study groups for lead & zinc and for copper, Joint Organisations Data Initiative of International Energy Forum, Extractive Industries Transparency Initiative, OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict Affected and High-Risk Areas,. However, no indications are provided concerning the achievements of these organisations. The possible inclusion of phosphate rock in the latter two is not discussed. The authors suggest that global phosphorus governance should include monitoring and better regulation of all levels of phosphorus extraction, use and destination: prospection and mining, processing, use, crop uptake, human and animal wastes …. The authors propose that the United Nations take the initiative of a white paper on phosphorus use, leading to a UN Convention establishing a phosphorus governance facility identifying minimum standards, promoting best practices and awareness raising. No example of comparable UN actions for other minerals is indicated or discussed.

"The governance gap surrounding phosphorus", A. Rosemarin, N. Ekane, Nutr Cycl Agroecosyst, 2015 https://doi.org/10.1007/s10705-015-9747-9

Eutrophication and phosphorus in the environment

Tomorrow's eutrophication challenges in Europe

- ***Summary of phosphorus – eutrophication priorities in Northwest Europe***
- ***Priority should be reducing phosphorus losses in catchment headlands***
- ***Climate change will accentuate P losses***

Bol et al. (2018) reviewed the challenges and priorities for addressing phosphorus-caused eutrophication in Northwest Europe. Point source phosphorus emissions have been considerably reduced over recent decades, but diffuse emissions from agriculture have decreased little or even increased. For NW Europe the regional impacts of climate change on soil P dynamics and losses are still not well understood, and will be complex as crops and agricultural practices as well as weather, hydrology and soil conditions are likely to change. For example, some models suggest that P loads to the Baltic will increase whereas N loads will decrease. Crucially, catchments which are already at high risk of phosphorus losses may be particularly responsive to climate change. Climate change can also increase soil erosion, thereby leading to P losses as particulate phosphorus. Understanding phosphorus losses, and defining appropriate mitigation practices, is complicated by remobilisation of P in water sediments, difficulties in monitoring phosphorus losses (especially of particulate P), because system P loss is a dynamic process with considerable time variation, and also changes in soil phosphorus forms are related to landscape management. This leads to difficulties in predicting catchment phosphorus "hot spots" and "hot moments". Overall, better information on colloidal phosphorus in soil is needed, because this form is both bioavailable and mobile. The need for joined-up research and management strategies, and the importance of better understanding of soil phosphorus forms and behaviours, are underlined and highlighted in the review.

"Challenges of reducing phosphorus based water eutrophication in the agricultural landscapes of Northwest Europe", R. Bol, G. Gruau, P-E. Mellander, R. Dupas, M. Bechmann, E. Skarbøvik, M. Bieroza, F. Djodjic, M. Glendell, P. Jordan, B. Van der Grift, M. Rode, E. Smolders, M. Verbeek, S. Gu, E. Klumpp, I. Pohle, M. Fresne, C. Gascuel-Odoux, Frontiers in Marine Science August 2018, https://doi.org/10.3389/fmars.2018.00276

See also "Dissolved and colloidal phosphorus fluxes in forest ecosystems – an almost blind spot in ecosystem research", R. Bol et al., J. Plant Nutr. Soil Sci. 2016, 000, 1–14 https://doi.org/10.1002/jpln.201600079

Climate change impacts on agricultural phosphorus losses

- ***In the UK climate change could increase P losses to surface waters by 10-30%***

A Lancaster University led study from 11 UK institutes models expected impact of climate change on agricultural P losses, based on high-frequency P flow data from three UK sub-catchments, a climate model and uncertainty estimates and two P transfer models (HYPE Hydrological Predictions for the Environment and DBM Data-Based Mechanistic). The three sub-catchments (Newby Beck, Cumbria – Blackwater, Norfolk – Wylye, Hampshire) have different agricultural contexts (livestock, arable). Results predict increased winter rainfall (+15 to +30%) and decreased summer rainfall. Because most P losses occur in winter, when soils are water saturated, this results in expected increases of +10 to +30% in annual P losses, despite a reduction in summer losses (-20%). These increases in P losses are greater than reductions estimated as possible by farm mitigation measures within current agricultural practice, and could only be countered by considerable agricultural changes (e.g. -20 to -80% reduction in P inputs).

"Major agricultural changes required to mitigate phosphorus losses under climate change", M.C. Ockenden et al., Nature Communications, 8:161, 2017, http://dx.doi.org/10.1038/s41467-017-00232-0 This summary was already published in ESPP eNews n°19.

Increases in phosphorus losses to and retention in freshwaters

- ***Annual losses of N and P to freshwaters worldwide nearly doubled over the twentieth century***
- ***Agriculture now represents over 50% of these N and P losses***
- ***N and P retention doubled (in rivers, dams and reservoirs)***
- ***Also nearly 400 mtN have accumulated in groundwaters worldwide***

Beusen et al. (2016) calculate changes in global phosphorus (N) and nitrogen (N) losses to freshwaters (rivers and streams), retention in sediments and final transfer to oceans. This is based on the IMAGE-GNM model which combines information on land use with the global hydrological model PCR-GLOBWB. They conclude that over the twentieth century worldwide nutrient losses to freshwaters increased from 34 to 64 million tonnes N per year (mtN/y) and from 5 to 9 million tonnes of P (mtP/y). Accumulation of N in groundwater worldwide is estimated at 376 mtN (total over 100 years). Agriculture's contribution to losses to freshwater over the century rose from 19% to 51% for N, and 35% to 56% for P. At the same time, nutrient retention in freshwaters increased considerably, from 14 to 27 mtN/y and from 2.6 to 5 mtP/y. 54% of this N retention occurred in rivers, and 63% of

P retention, the remainder in lakes and reservoirs. The authors consider that the development of dams and reservoirs today accounts for a significant part of this nutrient retention (24% and 22% of global N and P retention in freshwater systems). The increased retention did not balance the increases in inputs, so that final discharges to oceans also increased, from 19 to 37 mtN/y for N and from 2 to 4 mtP/y for P, leading to coastal eutrophication. Human activities have also led to a general increase in the N:P molar ratio in freshwaters, and an increase in the N:P ratio in rivers draining into most oceans (Pacific, Indian, Mediterranean and Black Sea, but not the Atlantic).

"Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum", A. Beusen et al., Biogeosciences, 13, 2441–2451, 2016 https://doi.org/10.5194/bg-13-2441-2016

Soil phosphorus balances for three river major river basins

- ***Phosphorus inputs to the Thames UK and Maumee USA river basins have considerably decreased since the 1980's***
- ***This is mainly due to lower mineral fertiliser use***
- ***Outflow of P in river water from these basins may today be similar or slightly higher than basin-wide net input***
- ***In the Yangtze basin China, however, phosphorus inputs continued to increase between 2000 and 2010***
- ***In the USA, no tillage and other practices may result in higher river soluble phosphorus***

Powers et al. 2016 use various data sources to estimate input to agricultural soils and compare to estimated outflows in river water in three very different river basins: Thames UK (12 000 km^2, population 3.8 million), Maumee USA MidWest (16 000 km^2, population <1 million) and Yangtze central China (1.8 million km^2, population 492 million). The authors derive phosphorus accumulation in the "landscape P pool" (soils and aquatic system) for 1940 (Thames), 1970 (Yangtze) or 1975 (Maumee) to 2010 by combining a range of published data sources, such as phosphorus outflow in river water, fertiliser imports, phosphorus in raw sewage, estimates of P import/export in crops, animal feed, manure, etc. Much of this is highly estimative: for example, for the Thames, the proportion of crop P exported from the farm is based on the national average of 44% of crop production going to animal feed, and the flux of animal feed P across the river basin borders is assumed to be zero. Estimates depend on the reliability of the data sources used, whereas the Thames estimates are largely based on the discredited Comber 2013 paper (see SCOPE Newsletter n°103). Given the very considerable changes in sewage works discharges into surface waters over the studied period (changes in phosphorus use in detergents, improvement of sewage treatment and P removal) and the high populations in the Thames and Yangtze basins, it is surprising that data for sewage works discharge P are not considered. The authors conclude that for the Thames and Maumee basins, net phosphorus exports have exceeded imports since the late 1990's. This conclusion seems rather presuming, in that Fig.2 shows very similar and fluctuating input/output, and considering the many highly estimative approximations used in deriving these numbers. Nonetheless, the study does show a clear fall in phosphorus inputs to the Thames and Maumee basins since the 1980's, resulting mainly from a reduction in mineral fertiliser use, compared to an ongoing increase in the Yangtze basin.

In a second paper, Jarvie et al. 2017 (several authors shared with the above paper), examine phosphorus flow data in the Maumee and in two other smaller rivers flowing into Lake Erie (Sandusky, Raisin), showing that both particulate and soluble reactive phosphorus (SRP) flows fell from 1985 to 2002, but then increased over the period to 2014. Based on modelling and land management data, they suggest that the very considerable increases in SRP may result from increases in no tillage and cover crops, which can retain phosphorus on the soil surface.

"Long-term accumulation and transport of anthropogenic phosphorus in three river basins", S. Powers et al., Nature GeoScience Letters 2016 https://doi.org/10.1038/NGEO2693 This paper is included because it won the ESA (Ecological Society of America) Biogeosciences Gene E. Likens award 2017. This paper is a US P-RCN outcome (SCOPE Newsletter n°125).

"Increased Soluble Phosphorus Loads to Lake Erie: Unintended Consequences of Conservation Practices?", H. Jarvie et al., J. Environ. Qual. 46:123–132 (2017) https://doi.org/10.2134/jeq2016.07.0248

Agricultural phosphorus losses and water protection policies

- ***Analysis of policies to address agricultural impacts on water quality***
- ***Includes indications of on-farm nutrient mitigation measures***
- ***Importance of agricultural practices, land use and cost allocation system***

McDowell et al. (2016) assess in detail and compare agricultural policies and practice addressing impairment of water quality by P in New Zealand, UK and USA, looking at regulation, incentives and voluntary approaches. Costs for a range of on-farm P mitigation measures and management practices are indicated. Uncertainty in estimating agricultural P losses and in linking these to management practices depending on local soil and other conditions is identified as a challenge to the development of effective policies. This makes it difficult to implement policies and measures such as fees per unit of P lost to surface water. Common between all three countries is an emphasis on discouraging or prohibiting bad management practices. The authors conclude that a mixture of mandatory and incentive measures is necessary to reduce agricultural P losses, with a fair mechanism to allocate costs. This requires implementation at the catchment level and the development of an evidence base for cause and effect, as well as appropriate sampling regimes to ensure compliance. In particular, better understanding is needed of how different farm practices impact P losses at the catchment level, especially in critical source areas susceptible to locally high losses. It is increasingly recognised that beyond farm practice policies, achievement of good water quality status will in some places require changes in land use.

"A review of the policies and implementation of practices to decrease water quality impairment by phosphorus in New Zealand, the UK, and

the US", R. McDowell, R. Dils, A. Collins, K. Flahive, A. Sharpley, J. Quinn, Nutr Cycl Agroecosyst (2016) 104:289–305 https://doi.org/10.1007/s10705-015-9727-0

Agricultural systems and policies

Improving phosphorus efficiency in livestock production

- ***70% of world meat production is poultry and pigs***
- ***Improving monogastric livestock phosphorus efficiency requires multidisciplinary approach***

Oster at al. (2018) summarise key questions around phosphorus use in monogastric livestock production (pigs and poultry), which impacts both phosphorus consumption and phosphorus content of manures. Only around 20% of phosphorus in mined phosphate rock reaches human food (Cordell 2009, Schroeder 2010, MacDonald 2012). Around 70% of world meat production is pigs and poultry, so phosphorus efficiency in this sector is very important. Aspects discussed include animal phosphorus metabolism, uptake of dietary phosphorus in monogastric livestock, animal feed composition, adaptation of feeding systems (e.g. dry feed for pigs seems to show lower P uptake), use of phytases to improve uptake, links to animal health (bone structure, endocrine response, immune system), livestock genotypes, losses in slaughterhouses (20-30% of pig and poultry animal weight goes to waste streams), manure phosphorus impacts on soil and losses to eutrophication, regulatory barriers to recycling and regulatory opportunities (e.g. EU renewable energy directive 2009/28 which leads to resource recovery opportunities in complement to energy production).

"Bridging Gaps in the Agricultural Phosphorus Cycle from an Animal Husbandry Perspective - The Case of Pigs and Poultry", M. Oster et al., Sustainability 2018, 10, 1825; http://dx.doi.org/10.3390/su10061825

Organic phosphorus forms in soils under different uses

- ***Soil organic carbon, inorganic P and different forms of organic P vary with intensity of farming***
- ***Intensive crop and grassland show lower organic carbon, less variety of organic phosphorus forms***
- ***Wide local variations within similar land use soils show need for locally specific management***

Stutter et al. (2015) compared organic phosphorus species in top soils (0-15 cm) from 32 sites in the UK under different land use, including arable, intensive grassland, extensive grazing, moorland, forest and arable buffer zones (rough grass). Soil parameters were measured in composite samples from an 8mx8m grid and included: total N, total C, Fe_{ox}, Al_{ox}, and different forms of inorganic and of organic phosphorus. Soil organic carbon ranged from 22 g/kg in arable soil, to around 50 in arable buffer and intensive grassland and nearly 160 in extensive/natural, whereas total P ranged from 1300 to around 1050 mgP/kgDM, and the proportion of total P in inorganic form from nearly ¾ to just over ¼. For all land uses, the monoester organic P / inorganic P ratio increased with higher soil organic carbon. The variety of organic phosphorus forms (diesters, polyphosphates, phosphonates) was also higher in less intensively used land, with nearly all organic P as monoesters in arable land whereas nearly 1/3 in other forms in extensive/natural soils. The authors conclude that intensive agriculture limits soil microbial function and so P species diversity, but that there is considerable variability in P forms within similar land use soils (probably related to local factors such as soil type and soil minerals, pH, hydrology, climate, crop type, use of organic fertilisers/manure …) so that soil P management strategies need to be locally adapted.

"Land use and soil factors affecting accumulation of phosphorus species in temperate soils", M. Stutter et al., Geoderma 257–258 (2015) 29–39 http://dx.doi.org/10.1016/j.geoderma.2015.03.020

Review of science on soil phosphorus activators

- ***Phosphorus activators can significantly increase plant availability and uptake of soil phosphorus***
- ***A wide range of P activators are available: micro-organisms, organic materials, organic and inorganic molecules***
- ***The risk of increasing phosphorus losses should be taken into account***
- ***Use needs to be adapted to local soil conditions, soil management practices***

Current knowledge on soil phosphorus activators is presented. Improving crop access to phosphorus in soils is important to enable use of accumulated P reserves in soils ("legacy phosphorus"), which it is suggested could sustain crop production for 100 years. More than 80% of P applied as fertilisers can be rapidly unavailable for plant uptake because of sorption or precipitation (in particular reactions with aluminium and iron ions in acidic soils and calcium in calcareous soils, or microbial immobilisation). Phosphorus activators are a range of different methods to facilitate plant P uptake. The following are presented (how they function, current development and knowledge): phosphorus solubilising micro-organisms (and different enzymes they release), organic matter, low molecular weight organic acids (carboxyl groups), humic acids and lignin, crop residues, manure biochars, zeolites, organic polymers and others. However soil P activators can also increase risk of phosphorus losses to surface and ground waters by dissolved and colloid P transport. P activator micro-organisms may also have biological impacts. A summary table of advantages and disadvantages of different types of P activators is provided. Use of combinations of activators can improve effectiveness, as can combination with appropriate soil management (e.g. tilling). Studies cited show considerable increases in both soil available phosphorus and soil P uptake into crops with different P activators.

"Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review", L. Zhu, M. Li, M. Whelan, Science of the Total Environment 612 (2018) 522–537 http://dx.doi.org/10.1016/j.scitotenv.2017.08.095

Global big data and the need for locally specific farm P policies

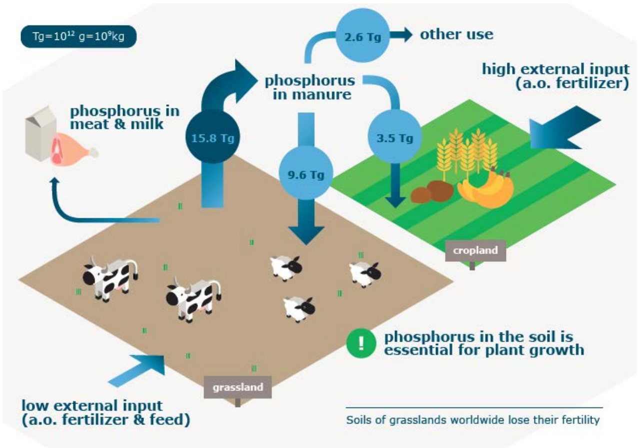
- ***Global data and regional studies should inform locally adapted policies and farm management***

Sharpley et al. (2016) emphasise that use of global big data on P, land use and management, and development of global and regional studies of stocks and flows of P, must inform – but not replace - local data on P management, which is based on practical realities of farming and catchment management. Macro-scale assessments and meta-analyses are valuable tools to inform policy and identify large-scale system disconnects, but their conclusions infrequently consider local environmental, agronomic, and social constraints. Logistics and economics are also critical: in particular, the objective of transporting P in manures from regions where amounts exceed local crop needs to regions of P deficit will require manure processing (to reduce transport costs). This additional cost will need to be taken into account in developing economically and environmentally sustainable solutions.

"Distant Views and Local Realities: The Limits of Global Assessments to Restore the Fragmented Phosphorus Cycle", A. Sharpley et al., Agric. Environ. Lett. 1:160024 (2016) https://doi.org/10.2134/ael2016.07.0024

Phosphorus offtake threatens sustainability of grasslands

- ***Phosphorus in the world's grasslands has been depleted because of under-fertilisation***
- ***Demand for grass for animal feed is projected to increase rapidly***
- ***Mineral fertiliser use on grasslands may increase to over half of total fertiliser use by 2050***
- ***This would contribute to doubling total mineral P fertiliser consumption by 2050***



Nearly 40% of livestock manure was exported away from the world's grasslands over 1970 – 2005, removing P and N and threatening grasslands fertility, according to a study published in Nature and based on FAOSTAT and IMAGE data. Many grasslands receive no or hardly any fertilizers resulting in negative P budgets. The world's grassland area is >3 billion hectares, twice the cropland area. Soil P removed from grassland must be replaced by organic and mineral fertiliser inputs in order to maintain or increase fertility. The authors estimate that to support an 80% increase in grass production, for milk and meat, these inputs will have to increase four-fold from 2005 to 2050. Combined with requirements for cropland, they estimate that total mineral P fertiliser use must double by 2050 (to 45 million tonnes P, 24 for grassland and 21 for cropland). They emphasise that a range of nutrient management strategies will be needed to meet this challenge, including manure reuse, reducing food losses, returning nutrients from other organic wastes to land, balanced P fertilisation as well as mineral fertiliser use.

"Negative global phosphorus budgets challenge sustainable intensification of grasslands", Sattari et al., Nature Communications 2016 http://dx.doi.org/10.1038/ncomms10696 *Open Access. Summary published I ESPP eNews* [n°3](#).

Fertilisers, yields and soil phosphorus ("legacy P")

Can crop yield be maintained at lower soil phosphorus levels?

- ***Agronomic recommendation to maintain Soil Olsen P Index 2 generally ensures no crop yield loss***
- ***In some circumstances, Soil P Index can be maintained at 1 if P fertiliser is appropriately applied annually***
- ***Soil P Index 2 may not be achievable on calcareous soils***
- ***1/5 of UK arable soil shows Soil P Index too low for optimum crop productivity***

Morris et al. 2017 (AHDB) publish further results and conclusions from field trials at six UK sites over six years (2009-2015) assessing current soil phosphorus management recommendations. These recommend to maintain soil Olsen P index 2. The sites had initially low soil P (15 mgP_{Olsen}/l or lower) with varying soil types. Rotations of arable crops, mainly wheat, barley and oilseed rape were grown. Results from 36 site-years show that maintaining Soil P Index 2 will ensure that crop yields "are not significantly limited by P availability" under a wide range of conditions, and that "Maintaining all fields at below soil Olsen P Index 2 … risks significant yield loss". However, in some circumstances, particularly where soil structure and crop rooting are good, maintaining Soil P Index 1 could be sufficient, if annual application of P fertiliser is ensured to fulfil crop needs. This is also applicable on calcareous soils, where establishing Soil P Index 2 may be difficult because of formation of poorly soluble calcium phosphate minerals in the soil. The authors note that PAAG 2016 suggests that 5% of UK arable soils are at P Index 0 and 16% at P Index 1. Even if P fertiliser was applied annually to crop needs, this would result in a loss of 30 000 tonnes/year of wheat crop (value up to 2.4 million UK£) per year.

AHDB Project Report No. 570 "Cost-effective phosphorus management on UK arable farms", Work Package 2: Critical levels of soil P", N. Morris, S. Knight, H. Philpott, M. Blackwell, December 2017 https://cereals.ahdb.org.uk/publications/2018/january/02/cost-effective-phosphorus-management-on-uk-arable-farms-(sustainable-p).aspx

World cereal production losses due to phosphorus limitations

- ***Soil P levels limit global cereal yields by 22 to 55%***
- ***One year's fertilisation could reduce these losses to 17-50%***

Kvakić, Pellerin et al. (2018) estimate current limitation of global production for three major cereal crops resulting from inadequate phosphorus supply (temperate winter wheat, maize, rice). Crop phosphorus demand is simulated using the

ORCHIDEE-CROP, QUEFTS (soil – yield), PHI (yield / P ratios) models and C:P stoichiometry. Phosphorus supply is estimated from models of available soil phosphorus for agricultural soils (Ringeval 2017) and potential root uptake (De Willigen 1994). Conclusions are that inadequate soil phosphorus levels result in potential world yield losses of around 22%, 55% and 26% respectively for winter wheat, maize and rice. However, these gaps could be reduced by 5-10% of crop yield by one year fertiliser application (i.e. gap change 22% -> 17% etc.). These estimated yield gaps are lower than e.g. Mueller 2012, which included limitations due to other nutrients, weeds, pests, etc.

"Quantifying the Limitation to World Cereal Production Due To Soil Phosphorus Status", M. Kvakić, Global Biogeochemical Cycles, 32, 143–157 http://dx.doi.org/10.1002/2017GB005754

"Phosphorus in agricultural soils: drivers of its distribution at the global scale", B. Ringeval et al., Global Change Biology, Volume 23, Issue 8, August 2017, Pages 3418-3432 https://doi.org/10.1111/gcb.13618

"Closing yield gaps through nutrient and water management", N. Mueller et al., Nature, 490(7419), 254–257 https://doi.org/10.1038/nature11420

Long-term field studies of phosphorus fertilisation

- ***Importance of long-term field studies***
- ***Phosphorus fertilisation and liming significantly increase crop yield***

Zicker et al. assess results of long-term field studies at two sites in Germany (Rostock since 1998, Freising since 1978) showing the effects of inorganic and organic phosphorus fertiliser inputs and of liming. Impacts on plant-available soils phosphorus are detailed (double lactate and calcium lactate extractable, DL-P and CAL-P). Indications of impacts on crop yields are provided. The absence of phosphorus input (for one year) showed to reduce maize yield by 10-15%, with even higher impacts on beet crops. Impacts on winter cereals are lower (c. 5%), probably because of their more extensive root system. Liming also increases crop yield (higher soil pH renders soil P more plant available). Overall however, crop yields vary mostly as a function of factors other than fertiliser application. This confirms the need for long-term (multi-decade) field studies, in order to better understand the impacts of fertilisers and soil phosphorus, independently of climate and other variations. In another paper, Ohm et al. present long term Organic Farming field studies (Thünen Institute, Trenthorst/Wulmenau, NW Germany, since 2001). The absence of P fertilisation (over the whole period, no inorganic fertiliser, no phosphate rock) leads to depletion of soil phosphorus (CAL-P) by 1.7 mgP/kg/y without manure input and by to 1.4 mgP/kg/y with manure return, despite recycling back into soil of non-harvested nitrogen-fixing crops and of crop wastes.

"Soil test phosphorus as affected by phosphorus budgets in two long-term field experiments in Germany", T. Zicker, S. von Tucher, M. Kavka, B. Eichler-Löbermann, Field Crops Research 218 (2018) 158–170 https://doi.org/10.1016/j.fcr.2018.01.008

"Long-term negative phosphorus budgets in organic crop rotations deplete plant-available phosphorus from soil", M. Ohm, H-M. Paulsen, J-H. Moos, B. Eichler-Löbermann, Agron. Sustain. Dev. (2017) 37:17 http://dx.doi.org/10.1007/s13593-017-0425-y

Soil legacy phosphorus overview

- ***Legacy P concept developed in the 1960's remains a key research and agronomic challenge***
- ***Soil legacy P represents in theory > 300 years of crop needs***
- ***Strategies to improve soil P pool uptake may have negative trade-offs***
- ***Joined-up research is needed***

Kamprath 1967 developed the concept of "Legacy Phosphorus", that is the soil P bank accumulated by fertiliser and manure application in many regions of developed countries. Menezes-Blackburn et al. (2017) review understanding and research perspectives on legacy phosphorus today. Analysis of ^{31}P-NMR data from 258 soils (41 publications) shows that on average nearly 60% of extractable soil P is inorganic and around one third is monoester organic (extractable = NaOH-EDTA: this is on average 55% of total soil P, from literature). This extractable soil P pool represents over 300 years of crop requirements (based on figures for crop offtake from Sattari 2016 – summary above). However, only a small part of this soil P is readily available to crops (Olsen P: 1.5 – 11%, Vance 2003). The authors review possible approaches to increase crop use of the soil P pool including reducing fertiliser application (would in time reduce agricultural productivity), rotation with crops which scavenge soil P (including cover crops in no-till), genetic crop modification (possible risks and possible trade-offs), use of microbes (biostimulants) and precision fertilisation techniques. A critical aspect is improving movement of P through the soil to the plant roots.

"Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: a review", D. Manezes-Blackburn et al., Plant Soil (2018) 427:5–16 https://doi.org/10.1007/s11104-017-3362-2

Vermont: an example of unsustainable soil P accumulation

- ***Livestock concentration linked to soil phosphorus accumulation, P-losses and eutrophication***

Wironen et al. (2018) show how, despite radical changes in agriculture and land use, P continues to accumulate in soils in Vermont State, USA, because of intensive livestock production, posing problems for water quality. Most of Vermont's forest was cleared in the nineteenth century, with dairy farming then dominating. Since the mid twentieth century, small hill farmers have mostly disappeared and land use has returned to 80% forest. However, dairy production has doubled and today accounts for 80% of farmed land, with 85% of dairy products exported out of the State. The dairy farming is concentrated in the Champlain Lake and Lake Memphremagog basins, which both face eutrophication challenges with TDML phosphorus limits. This study is based on the Vermont phosphorus PFA, which estimates P flows at county and State levels using US Census of Agriculture data from 1925 to 2012. Over this period, Vermont has constantly had a State P surplus > 1 000 tP/y, peaking at > 4 400 tP/y in 1950. Since that date, State fertiliser use has dropped considerably but imports of P in cattle feed have increased (today these are three times higher than P fertiliser use) and Vermont still had a 1 400 tP/y surplus in 2012. State dairy PUE (P use efficiency) has considerably improved but animal density has increased 250% and Vermont soils continue to accumulate P at > 5 kgP/ha/y. The case of Vermont illustrates the challenges to eutrophication restoration posed by increasing livestock concentration and P trade in animal feeds.

"Phosphorus flows and legacy accumulation in an animal-dominated agricultural region from 1925 to 2012", M. Wironen, E. Bennett, J. Erickson, Global Environmental Change 50 (2018) 88–99 https://doi.org/10.1016/j.gloenvcha.2018.02.017

Potential for soil P drawdown and P loss reduction

- ***Reduction of soil P levels in the Chesapeake Bay catchment could reduce P losses by 40%***
- ***This would however take decades***
- ***With other measures, up to 62% reduction is compatible with modern agriculture***

The APLE (Annual P Loss Estimator) model was used to estimate phosphorus losses from agricultural soils in the Chesapeake Bay catchment, USA, a highly eutrophication-sensitive water body. APLE is spreadsheet based and designed to be easy to use with limited data input (soil Mechlich-3 P, soil clay and organic matter, precipitation, soil erosion loss, fertiliser, manure, tillage and crop data). Model estimates for soil phosphorus level reductions (drawdown) were validated by comparison to measured drawdown data from a 22-year study at three Maryland test sites (Fiorellino 2017). The APLE model was also verified by comparison to Chesapeake Bay Model results. APLE estimated current soil P losses at 0.8 - 0.9 kg P/ha/year, of which 10-70% is dissolved P, depending on soil P level and erosion rate. The analysis concludes that soil phosphorus losses could be reduced by 40% through soil P drawdown by crop offtake and no P inputs, but this process would take several decades. Combining soil P drawdown with aggressive conservation efforts to reduce erosion losses could achieve a 62% reduction in P losses to surface waters, considered to be a maximum achievable that is also compatible with modern agriculture in the area.

"Estimating Legacy Soil Phosphorus Impacts on Phosphorus Loss in the Chesapeake Bay Watershed", P. Vadas et al., J. Environ. Qual. 47:480–486 (2018) http://dx.doi.org/10.2134/jeq2017.12.0481

Legacy soil phosphorus and critical soil P

- ***P accumulated in agricultural soil before 2008 is estimated at 40x today's annual fertiliser use***
- ***Some accumulation is necessary to ensure available P for crops***
- ***But legacy P also results in losses, contributing to eutrophication***
- ***Research is needed to reduce legacy P whilst ensuring crop productivity***

Rowe et al. (2016) discuss the significance of P accumulated in agricultural soils ("legacy phosphorus"). They cite Sattari et al. (2012) who estimate that from 1965 to 2007 some 815 million tonnes of P accumulated in soils worldwide, compared to today's world phosphate fertiliser use of c. 20 mtP/y. Legacy P levels are however locally variable, depending on past P application, in manures or fertilisers, and on crop uptake. The authors recognise that some soil P accumulation above 'natural' levels is necessary to provide soil P fertility sufficient for supplying readily available P for crops, this is the concept of the critical soil phosphorus level beyond which additional phosphorus does not significantly increase crop yield (see Johnston in SCOPE Newsletter n°98). Crop-available phosphorus in soil can also be increased by e.g. liming or increasing soil organic matter. The authors note that soil legacy P results in a continuous loss of P to surface water, so contributing to eutrophication problems, but also to ground water, which contributes to river base flows and so to summer eutrophication risk. Strategies to reduce legacy P are discussed including progressive draw-down by crop uptake by adapting fertiliser application to match both plants' short-term needs (labile P) and longer term needs (slow uptake of less labile legacy P) and cropping systems designed to improve P uptake (e.g. soil management and cropping sequences, plant breeding, microbial engineering). Appropriate actions will be locally specific. To support action, research needs identified include better data on soil P and innovative soil tests to characterise soil P buffering capacity and P availability as soil P levels are reduced, market and policy levers, crop engineering, soil restoration, knowledge transfer and farm decision support tools.

"Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water Security", H. Rowe et al., Nutr Cycl Agroecosyst (2016) 104:393–412 http://dx.doi.org/10.1007/s10705-015-9726-1 This paper is a US P-RCN outcome (SCOPE Newsletter n°125).

Build-up of soil phosphorus during the twentieth century

- ***Estimates phosphorus accumulation in soils on different countries and global regions***
- ***Soil P increased over 30% in Europe from 1900 to 2010***
- ***Fertiliser P demand will have to double or triple to 2050 to maintain crop and grassland productivity***

Zhang et al. (2017) models changes in cropland soil P inventories calibrated from historical countrywide crop uptake, using the 0.5 x 0.5 degree "Dynamic Phosphorus Pool Simulator" (DPPS) for the period 1900–2010 (extended from Sattari et al., PNAS, 2012). The model considers labile and stable P in cropland top soils. National average fertiliser use is assumed on all cropland, and manure application is based on livestock manure production limited to regions with mixed livestock – crop systems. Simulated crop P uptake is calculated by both soil properties (available P and the P retention potential) and crop characteristics (maximum uptake). Global P inputs (fertiliser plus manure) increased from 2 mtP/y in 1900 to 23 in 2010. The study suggests that globally, the total P pool per hectare increased rapidly between 1900 and 2010 in soils of Europe (+31%), South America (+2%), North America (+15%), Asia (+17%), and Oceania (+17%), but has been stable in Africa. This would suggest that until 1950, P fertilizer application had a negligible influence on crop uptake, but recently it has become a driving factor for food production in industrialised countries and a number of transition countries, e.g. Brazil, Korea, and China. This comprehensive and spatially explicit model can be used to estimate how long surplus P fertilisation is needed or how long depletions of built-up surplus P can continue without affecting crop yield. In a further paper, Mogollón et al. (2018) use this DPPs model to estimate future global fertiliser P demand for different socioeconomic pathways, concluding that different such pathways lead to similar P demand, with P fertiliser demand for croplands increasing from 14.5 mtP/y in 2005 to 22-27 mtP/y by 2050, plus in 2050 4-15 mtP/y fertiliser needed to maintain fertility in farmed grasslands.

"Spatiotemporal dynamics of soil phosphorus and crop uptake in global cropland during the 20th century", J. Zhang et al. Biogeosciences 14, 2055-2068 https://doi.org/10.5194/bg-14-2055-2017

"Future agricultural phosphorus demand according to the shared socioeconomic pathways", J. Mogollón et al., Global Environmental Change 50, 149-163, 2018, https://doi.org/10.1016/j.gloenvcha.2018.03.007

Phosphorus in food and phosphorus applications

Overview of phosphorus, nitrogen and health impacts

- ***Health risks from N and P in drinking water are considered low***
- ***Most nitrate intake comes from fruit and vegetables, and intake is higher for vegetarians***
- ***No evidence of health risks from average diet phosphorus intakes***

A review of "Soil components and human health" summarises current knowledge on reactive nitrogen and phosphorus: nutrient cycles, losses to waters, health implications. Global input of N to agriculture is over 170 TgN/year, of which more than half leaks to groundwater. Global losses of particulate and dissolved P to surface water are estimated at 22 and 3 TgP/year. Phosphates are noted to not pose a risk in drinking water (no standards are fixed) but P levels in surface waters can contribute to algal blooms and algal production of cyanotoxins. These are irritant and allergenic, and questions are raised concerning possible carcinogenicity of low levels in drinking water (for e.g. microcystins, cylindrospermopsin). On the other hand, nitrates are limited by drinking water standards: although nitrate is considered non-toxic, there are concerns because of its conversion to *N*-nitroso compounds (by reactions in the gut) or to nitrites (around a quarter of ingested nitrates are excreted via the salivary glands, and part is then reduced in the mouth to nitrites). Some *N*-nitroso compounds may be carcinogenic, and nitrites interfere with haemoglobin (blood oxygen transport). On the other hand, recent studies suggest that nitrates may provide benefits in protecting against cardiovascular disease and infections. Most nitrates intake comes from fruit and vegetables (only 14 or 22% from water in the UK and France) and vegetarians' nitrate intake is 2-4 times higher than non-vegetarians'.

Other chapters in this Springer 2018 book provide information about dietary sources of phosphorus intake. P in meat and meat products is readily absorbed by the body, but only about half of the P in plants in foods is absorbed. The average adult P intake in diet is usually 1-2 gP/day and the editors consider that there is no evidence of adverse effects associated with the current intakes of P. The book also reviews the availability of P in soils, P cycling in the soil-plant system and the global P budget.

"Reactive Water-Soluble Forms of Nitrogen and Phosphorus and Their Impacts on Environment and Human Health", ch. 5, pp 233-255 https://doi.org/10.1007/978-94-024-1222-2_5 Summary published in ESPP eNews n°20 in R. Nieder, D. Benbi, F. Reichl, Springer book, 2018, "Soil Components and Human Health" https://www.springer.com/us/book/9789402412215

Dietary phosphorus and health

- ***Principal sources of P in USA diets are dairy products and meat based products, both around 20% each***
- ***Normal human serum (blood) phosphorus levels are 2.5 – 4.5 mmol/l***
- ***Cohort studies suggest that serum phosphorus is correlated to risk of cardiovascular disease (CVD)***
- ***No clear evidence of correlation between dietary phosphorus intake and CVD***
- ***No clear evidence of other health impacts of diet phosphorus***
- ***P intake is critical for CKD (kidney disease) patients, that is 26 million people in the USA***
- ***Some authors call for labelling of phosphorus levels in food products***

Two recent books provide wide reviews and information on current knowledge on phosphorus in food, levels of phosphorus in diet and dietary recommendations, possible impacts of levels of dietary phosphorus on health, and on use and functions of phosphate food additives: CRC 2018 and Humana/Springer 2017. The CRC 2018 book includes a review of papers relating phosphorus in diet to health (mainly papers 2013 or older), concluding that several cohort studies suggest correlations between blood phosphorus levels and heart disease (CVD cardio vascular disease), in both healthy individuals and kidney patients. This paper also shows a very small number of studies comparing blood phosphorus to other health endpoints. Other papers in the book show that there are very few studies comparing dietary phosphorus intake to heart disease. A review of 13 studies suggests that diet phosphorus does not modify blood pH (contrary to the acid-ash hypothesis). Availability of phosphorus in food is addressed, showing that only 1/3 – 2/3 of P in vegetable foodstuffs is absorbed into the body. Several papers note the lack of or inaccuracy of information about P content of food products and the book editors call for labelling of food phosphorus content, to provide essential health information, especially to kidney disease patients (26 million people in the USA). The Springer 2017 book presents current knowledge of phosphorus homeostasis in the body, including gut absorption and hormonal controls, and includes a detailed presentation of the chemical formulas and food improvement or protection functions of 24 phosphate food additives (inorganic sodium, calcium, potassium, magnesium and aluminium phosphate salts).

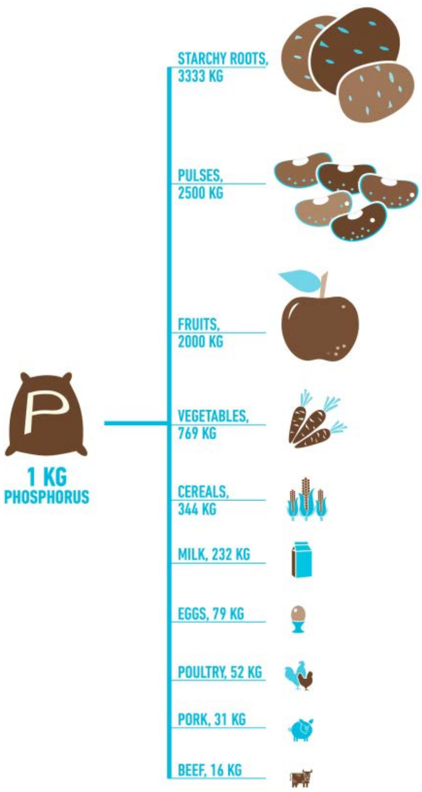
"Dietary Phosphorus: Health, Nutrition, and Regulatory Aspects", ed. J. Uribarri & M. Calvo, CRC Press 2018, ISBN 13: 978-1-4987-0696-4, 370 pages https://www.crcpress.com/Dietary-Phosphorus-Health-Nutrition-and-Regulatory-Aspects/Uribarri-Calvo/p/book/9781498706964

"Clinical aspects of natural and added phosphorus in foods", Humana Press (Springer), 260 pages, O. Gutiérrez, K. Kalantar-Zadeh and R. Mehrotra, editors. www.springer.com/us/book/9781493965649

Impact of diet on phosphorus sustainability

- ***Levels of meat consumption in diet considerably impact phosphorus footprint***
- ***Meat consumption estimated to account for over 70% of global phosphorus use***
- ***Questions remain concerning calculation of P-use in grass as animal feed, and recycling of P in manures***

Metson et al. (2016) analyse the impacts of dietary choice on P footprints and on potential for P-recycling, taking the case of Australia. This is based on the P footprint of different diets calculated in Metson et al. (2012). On this basis, Australians currently ingest around 0.67 kgP/y (1.8 g /day), but have a P footprint (see below) seven times higher, at 4.9 kgP/y. The authors estimate this to be three times the footprint needed for a plant-based diet with the same protein content, despite the calculation suggesting that a vegetarian would have a slightly higher P-content (+8%), and so excreted P (NOTE: nutritionists suggest however that vegetarian diets have lower P intake). Thus, moving to a vegetarian diet in Australia could potentially reduce the mined phosphate rock needed to produce food (-72%), whilst also slightly increasing the P-recycling potential in sewage (+8%). The authors note that dietary choices other than meat intake may also influence P footprint, for example choosing locally produced food may reduce food waste P losses, but may also facilitate sustainable farming practices with less soil P losses.



This paper (2016) is based on the methodology presented in Metson et al. (2012) in which P footprints are calculated for fifteen different foodstuffs/crops. These are based on PUEs (phosphorus used efficiencies) calculated for each foodstuff by dividing the estimated crop P content (FAO crop production data, USDA and NRCS data on P content) by P applied as fertiliser (IFA data). For animal products, the calculation is based on the amount of feeds needed to produce each kilogram of product and the P used calculated as above to produce the feed crops. On this basis, the authors conclude that meat consumption accounts for 72% of the global food P footprint and that increasing meat consumption accounted for 28% of the increase in global phosphate rock consumption since 1961 (the remainder resulting from population increase). National diet P footprints calculated vary from over 6 kgP/person/year in Argentina and the USA to around 1 kg in India or Ghana. Since 1961, some countries' P footprint has decreased slightly, whereas China's has increased +400%.

From this 2012 paper, the diagram and figures are derived at http://www.mcgill.ca/research/files/research/mcgill_headway_7-1_spr13_web_opt1.pdf (2013) showing how many kilogrammes of different food products can be produced from 1 kg phosphorus input.

ESPP editor's notes: in the above calculation approach, use of grass as feed is not considered in the PUE, making it an overly conservative approach, because many pastures are in fact fertilised. Sattari et al. (see SCOPE Newsletter n°106) have shown the significant demand of P for grassland. This is corrected in a further paper currently in press (Sydney). Furthermore, the Metson et al. P footprint calculation approach raises questions concerning 'transfer' of P from livestock production to crop production: if animal manure is used to fertilise crops (other than animal feedstuff production) then the P will be calculated as consumed in the livestock production, whereas it should be accounted to the crop production. A different calculation approach is taken by Helin & Weikard, (referenced below, paper not yet published), who conclude that P demand resulting from livestock production worldwide is somewhat lower (around half of total global demand) but confirm that changes in diet are a significant driver for P demand.

"Potential impact of Dietary choices on Phosphorus recycling and Global Phosphorus Footprints: the case of the Average Australian city", G. Metson, D. Cordell, B. Ridoutt, Front. Nutr. 3:35 (2017) *https://doi.org/10.3389/fnut.2016.00035 See also summary in ESPP eNews n°4.*

"The role of diet in phosphorus demand", G. Metson, E. Bennett, J. Elser, Environ. Res. Lett. 7 (2012) 044043 (10pp) *https://doi.org/10.1088/1748-9326/7/4/044043*

"A model for estimating phosphorus requirements of world food production", J. Helin & H-P. Weikard, Wageningen University Netherlands Seminars of the Economics Section 2015 (not published) https://www.wur.nl/en/Expertise-Services/Chair-groups/Social-Sciences/Section-Economics/Seminars.htm

Calcium phosphates reference work updated

- ***Updated reference work on calcium phosphates biology, chemistry and applications***

Sergey Dorozhkin's 2017 four-volume book on calcium phosphates (2017) provides up to-date publications on calcium phosphate chemistry, biology, applications, uses and perspectives. This updates his 2014 books (see SCOPE Newsletter n°102) integrating reference papers published since then. There are 1500 pages, 200 figures and tables and 8100 references. The books cover hydroxyapatite and other calcium phosphates, including history, ceramics, bio composite's, dental applications, crystallisation, chemistry and nano forms.

"Hydroxyapatite and other calcium phosphates" 1-4, S. Dorozhkin, Nova Science Publications *www.novapublishers.com/catalog/product_info.php?products_id=61821&osCsid=d736ddbd5b7197b232a73b84ff785d4a*