SCOPE NEWSLETTER

European Sustainable Phosphorus Platform

Legacy Phosphorus in agricultural soils: Maintaining crop yields and minimising losses to water

This SCOPE Newsletter summarises the **ESPP – BOKU webinar, 2nd February 2022, on "Legacy Phosphorus"** and a selection of recent, relevant scientific publications.

Please see also the SPA (US) webinar "A Legacy of Phosphorus", 30th September 2021, summarised in ESPP eNews n°59, and the Frontiers in Earth Science special summarised in ESPP eNews n°56.

For an overview of phosphorus in soil, see Leo Condron's New Zealand Society of Soil Science (NZSSS) "Normal Taylor" lecture (1 hour) here https://www.youtube.com/watch?v=uNuCifqpeH0

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Slides, abstracts, edited Chat and full video recording of the webinar are online here: *www.phosphorusplatform.eu/LegacyP*

Lexicon

To facilitate reading, the terms below are used as follows throughout this SCOPE Newsletter:

'**Phosphorus losses**": the term "phosphorus leaching" is often used in papers and presentations = all phosphorus losses from fields to surface waters, via runoff, sub-surface water movement, tile or surface drains …

PSI = **Phosphorus Saturation Index** (or PSR, Phosphorus Saturation Ratio)
= molar ratio of (Mehlich-3 phosphorus) / (Mehlich-3 iron plus Mehlich-3 aluminium) = P/(Fe+Al) see Chardon et al. 2000

Mehlich P = Mehlich-3 or Mehlich-III (***NOTE***: *in this Newsletter, unless specified otherwise "Mehlich P" means Mechlich-3, not Mechlich-1 or Mehlich-2 which extract different phosphorus pools)*

P_{AC} = ammonium citrate extractable P

P_{-Al} = ammonium acetate lactate extractable P

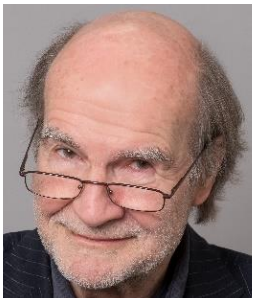
P_{-ox} = oxalate extractable P

$P\text{-}CO_2$ = CO_2-saturated water extraction

$NaHCO_3$-P = sodium bicarbonate extractable P

WEP = **Water Extractable Phosphorus** (mg/kg) = Water Soluble P = WSP or P_{-W}

Editorial



Over 560 online participants for the ESPP-BOKU webinar on "Legacy Phosphorus", the previous Sustainable Phosphorus Alliance webinar. The many scientific publications over recent years, show the ***considerable current interest*** *for this question (see e.g. Jarvie et al. 2-page discussion paper, 2013)*

Much of the scientific literature suggests that soil phosphorus can be reduced without deteriorating crop productivity (e.g. the editorial of the Frontiers in Earth Science special on Legacy P summarised in ESPP eNews n°56).

However, not only do many studies show that P application (as fertiliser or manure) is essential for crop yields, but also some of the long-term field trials presented at this webinar show that ***draw-down of 'Legacy' P led to lower crop yields*** *(Regelink, Shober, Nair, see also Nawara in ESPP eNews n°48) unless initial soil-P is high (above agronomic recommended levels), or in some cases lower yields for some crops or over the long term (Cade-Menun), or to lower P-content of crops (Van Rotterdam). Some of the studies claiming that soil P levels can be reduced without impacting crop yield are at high P levels above the agronomic recommendation so that no benefit of higher P is to be expected (Zhang below).*

An important conundrum identified is that lower soil P may not result in a "statistically significant" loss of crop yield, because of high variation in harvests between plots and years, with natural variations and in particular weather (Braun, Ylivainio), whereas a ***5-10% loss in crop is an unacceptable economic loss for farmers and for food production****.*

For the farmer, it can be economical to apply high fertiliser levels even if these are only effective in years with good weather conditions, resulting in excess nutrient application many years.

Another conundrum is that ***the agronomic optimum soil P level for crop production is generally considerably higher than the threshold for environmental protection*** *to limit P losses. In some cases, even balanced P fertilisation can result in P losses posing eutrophication risk (Watson below). There is a critical soft-spot for soil P management between these two thresholds. The decision to risk lower crop yields, in order to reduce P losses, should be political and societal and depend on local conditions (e.g. water body eutrophication sensitivity, biodiversity, climate). Farmers will need to receive financial compensation if soil P levels are reduced below agronomic optima. Reducing P losses to zero is generally incompatible with productive agriculture (e.g. Vadas in SCOPE 128).*

ESPP draws the following conclusions:

- *Addressing "Legacy Phosphorus" is important to protect surface waters from eutrophication, now and in the future, and to improve phosphorus stewardship*
- *In some regions, phosphorus has been, or continues to be, accumulated in soil above agronomic recommended levels, usually because of livestock density and manure application (e.g. Vermont, see Wironen I SCOPE 128). In such cases, phosphorus draw-down will reduce P losses without impacting crop productivity;*
- *In much of the world, especially tropical soils, the challenge is to access phosphorus in soils which is poorly plant available and bound to soil minerals such as iron (can be termed "natural Legacy P");*
- *R&D is needed on approaches to improve crop access to poorly-available P forms in soil. This will address both*
    - *the 'soft spot' between agronomic and environmental soil P thresholds,*
    - *and access to P in tropical soils;*
- *Climate change will accentuate Legacy P challenges, as variable weather will result in under-use of P by crops and will increase P losses (see SCOPE 127)*
- *Clarification of the definition(s) of "Legacy Phosphorus" is important, to improve communication between researchers, regulators and farmers.*

Ludwig Hermann, ESPP President

Defining “Legacy P”

At the ESPP – BOKU webinar, 2nd February 2022, it was underlined by a number of participants that at present “Legacy Phosphorus” can mean different things to different people, and that this generates obstacles to addressing the real challenges of ensuring crop production whilst minimising P losses and stewarding P resources.

A mass balance definition …

Opening the webinar, **Phil Haygarth** proposed (see below) a simple definition of “**Legacy P**” as the accumulation over time of:

+ **inputs** (fertilisers, manure …)
- **offtake** (in crops)
- **losses** to surface and ground waters
- **indigenous P**

Unfortunately, Legacy P as defined above cannot be determined. Even if long-term data was available on P inputs and offtakes, full information is always missing to quantify P losses. Thus, Legacy P as defined above can only be estimated by modelling. From a practical point of view, Legacy P as defined above is the **difference between natural soil P and current total soil P**.

This definition assumes other inputs (agrochemicals, atmospheric deposition …) are not significant. It also eludes the question of to what depth “soil P” should be measured.

… but how can this be measured

This is however complex to quantify. **Should we measure only P in the topsoil (maybe 0 – 15 cm) or also P deeper in soil? How should we measure soil Legacy P, given that soil P tests (e.g. Olsen P, Mehlich P) measure only plant available P** whereas much of the P stored in soil may evolve towards non-available forms?

An agronomic definition

A second definition of "Legacy P" could be to **consider only P accumulated in soil to above the agronomic recommended level**, assuming that this is the minimum to maintain crop yield close to maximum. This definition could be considered more practically useful to farmers and policy makers, who generally do not wish to reduce food production.

Such a definition, however, would be dependent on the pertinence of agronomic recommendations for soil P, which are at best approximate, are often presented as wide ranges. As discussed below, **agronomic recommendations for soil P are in cases outdated and are rarely locally adapted**.

Furthermore, agronomic recommendations generally address only plant available P, so such a definition would fail to encourage improvements of crop uptake of poorly available soil P, for example by crop breeding, biostimulants or management practices.

An environmental definition

As seen below, agronomic recommended levels are generally significantly higher than P-loss thresholds, even if comparison may be difficult if they are not expressed using the same P measurement method (e.g. Olsen P vs. WEP).

Another definition of “Legacy P” could be **soil P above the threshold for environmental loss**, but with similar limitations as for the definition above based on agronomic recommended soil P levels.

This discussion does however draw attention to the **critical soft-point for soil P levels, between the environmental loss threshold and the agronomic recommendation**. Above the agronomic recommendation, farmers will see the interest to draw-down P. But below this recommendation level, there is a conflict between risk of losing crop yield and risk of eutrophication.

An opportunity definition

As emphasised by **Achim Dobermann** (see below) and others, worldwide including in some parts of Europe, **many soils hold a considerable pool of natural P which is not readily plant available** (can be called “**natural Legacy P**”).

Accessing this natural reserve of phosphorus would enable increased yields and food production, reduce need for mineral fertilisers, and so reduce environmental risks.

The same techniques may help access “natural Legacy P” and reduce risk of P losses in well fertilised soils (in the soft-spot between agronomic recommendation and P-loss threshold). Techniques such as crop breeding to improve root P access and P uptake, biostimulants, agronomic management techniques need to be developed, but together with a holistic approach

ESPP – BOKU webinar on Legacy Phosphorus

Slides, abstracts, edited Chat and full video recording of the webinar are online here: www.phosphorusplatform.eu/LegacyP

Over 560 participants joined the ESPP- BOKU webinar on the impacts of reducing "Legacy Phosphorus" in agricultural soils, 2nd February 2022, with a very active oral and online chat discussion. The webinar was chaired by **Steve Hallam, International Fertiliser Society** (IFS), **Christiana Staudinger and Jakob Santner, BOKU** (University of Natural Resources and Life Sciences, Austria) and **Ludwig Hermann, ESPP President**.

This SCOPE Newsletter special issue documents this webinar and also summarises a selection of recent scientific publications relevant to "Legacy P".

This ESPP webinar follows on from the SPA (US) webinar "A Legacy of Phosphorus", 30th September 2021 summarised in ESPP eNews n°59, , and from the Frontiers in Earth Science special summarised in ESPP eNews n°56 (six articles on 'Legacy Phosphorus' by Gatiboni, Zhang, McDowell, Messiga, Soltangheisi and De Souza Nunes).

An outcome from discussions at the ESPP – BOKU webinar was the identified need to define and agree, between different scientists and stakeholders, a consensus definition of "Legacy Phosphorus", in order to clarify the use of the term in agronomic, policy and scientific discussions.

Panelists' points

Jim Elser, Sustainable Phosphorus Alliance, Arizona State University, USA: *Above all, we need to keep the Legacy P in soil out of surface waters, to avoid long-lasting eutrophication impacts.*

Antonio Delgado, University of Seville, Spain*: Climate change will increase the challenge, unexpected weather conditions will mean P is applied to fields but then not taken up by crops.*

Marzena Smol, Polish Academy of Sciences*: Surveys show that many farmers in Poland continue to use fertilisers more than required. We need to communicate good practices, and further new policy recommendations are required.*

Leonardus Vergutz, Mohammed VI Polytechnic University, Morocco*: Is Legacy P good or bad? In much of the world, soil P needs to be built up to support food production, particularly in the tropics but also in temperate regions.*

Kari Ylivainio, Natural Resources Institute Finland (LUKE)*: Improving P use efficiency or adding P to animal feed can reduce pressure on fodder crop P content, and so on fertiliser use.*

Luke Gatiboni, North Carolina State University, USA*: With the current fertiliser price increase, farmers are currently motivated to optimise nutrient application. Now is the time to change farmers' habits.*

Different visions of 'Legacy P'

Phil Haygarth, Lancaster University, UK, opened the webinar by questioning what is meant by "Legacy Phosphorus". This is a relatively new term, which has appeared mostly over the last decade. The definition is not simple or agreed (see above), but certainly **the term is helpful in bringing attention to a critical environmental challenge for agriculture**.

Today, "Legacy Phosphorus" poses unanswered questions: How to reduce agricultural phosphorus losses to surface waters (leading to eutrophication)? How to use soil-stored phosphorus for food production?

Andrew Sharpley, University of Arkansas, USA, noted the difficulties of managing Legacy P. Understanding phosphorus behaviour, over time, in soils and water systems is complex. The transfer time of P from field to surface water is variable and difficult to predict, as is the retention or release of P in streams and drains.

Phosphorus traps such as vegetation buffers or constructed wetlands can transition to become P sources, so require monitoring and adaptive management over time.

Once P has entered the field – water system, its transport and fate are difficult to predict and to manage, so **the key must be to limit P application rates, based on soil P testing and on agronomic recommendations**.

Achim Dobermann, IFA (International Fertilizer Association), indicated that **sustainability is today necessary for the fertiliser industry**, with the aim of managing nutrients in the whole field to fork food system. Using historically accumulated phosphorus in soil can contribute to this.

He suggests that two different forms of "Legacy Phosphorus" must be considered:

- In some regions, **historical high application levels of manure and/or fertiliser** result in soil P levels which pose risks of losses to surface waters (and environmental damage through eutrophication). This offers an opportunity to use this accumulated P
- **In much of the world, significant stocks of phosphorus are indigenous phosphorus in soil in forms which are recalcitrant to plant uptake. This can be considered as "natural Legacy P"**. We need to access this phosphorus, and prevent loss of applied fertiliser P to such forms, to enable food production.

In both cases, "Legacy P" is in complex forms in the soil, not readily accessible by current crops and farming methods. Holistic approaches are needed to address this, and to improve crop use of soil Legacy P, combining use of microbes and biostimulants, plant breeding, spatial management of crops and precision application of phosphorus fertiliser. This will require field-based, interdisciplinary science, including engaging with agricultural economists.

Modelling the time needed for P "draw-down "

Rich McDowell, AgResearch: New Zealand, presented results of modelling based on 500 000 soil Olsen-P data points across New Zealand. Soil water extractable P was estimated based on Olsen-P and soil characteristics. Agronomic target limits for soil Olsen-P were defined based on soil type and land use, 18 – 40 mg/l Olsen-P, and an environmental target limit for WEP (Water Extractable Phosphorus) of 0.02 mg/l was defined considered appropriate to avoid P losses.

Around 45% - 75% of soils in dairy systems were exceeding the agronomic soil P target by 2002-2015, and 10-30% in sheep and beef systems, in both cases nearly twice the proportions in 1988-1996. Exceedance of agronomic P targets was significantly greater in volcanic and sedimentary soils (compared to peat and pumice).

Time necessary for soil P to be drawn down to agronomic or environmental targets were modelled, assuming P offtake with grazing/cropping and no fertilisation.

Time to draw-down P to agronomic target levels was less than a year for ¾ of sites, but nearly 12 years in some cases.

Time to draw-down P to the environmental target (WEP) was however > 26 years for half the sites and > 55 years for a quarter of the sites.

See: "The Ability to Reduce Soil Legacy Phosphorus at a Country Scale", R. McDowell et al., Front. Environ. Sci. 8:6 2020 https://doi.org/10.3389/fenvs.2020.00006 (see ESPP eNews056)

Field tests of “P mining” and crop yield

Inge Regelink, Wageningen University Research, Netherlands, presented results of **10 – 17 year field tests at four locations in The Netherlands** comparing grass yield with or without fertiliser application: Zegveld (peat soil), Heino and Soerendonck (sandy soil) and Lelystad (clay soil). On P-fertilised plots, manure was applied to balance P offtake, whereas on no-P plots mineral N fertiliser but no P fertiliser was applied. Initial soil P was close to the agronomic recommended level.

After ten years without fertilisation, grass crop yield was around 40% lower than on fertilised plots in tilled, sandy soils and around 60% lower in permanent grassland on clay and peat soils.

The initial P$_{\text{-Al}}$ (ammonium acetate lactate P) in the permanent grassland on sandy and tilled clay and peat soil was similar in the top 0-5 cm, but two to three times lower at 5 – 30 cm depth in the permanent grassland. The lower crop yield loss in the tilled clay and peat soils may be due to “mining” of phosphorus from these lower soil layers by crop roots in the tilled soils.

These results show the **need to consider tillage, soil characteristics and P levels across the soil depth profile** when discussing “Legacy Phosphorus”.

van der Salm, C., van Middelkoop, J.C., Ehlert, P.A.I., 2017. Changes in soil phosphorus pools of grasslands following 17 yrs of balanced application of manure and fertilizer. Soil Use Manag. 33, 2–12. https://doi.org/10.1111/sum.12333

van Middelkoop, J.C., van der Salm, C., Ehlert, P.A.I., de Boer, I.J.M., Oenema, O., 2016, Does balanced phosphorus fertilisation sustain high herbage yields and phosphorus contents in alternately grazed and mown pastures? Nutr. Cycl. Agroecosystems 106, 93–111. https://doi.org/10.1007/s10705-016-9791-0

Regelink, I.C., Van Middelkoop, J., Geel, W. van, Ehlert, P.A.I., 2021. De enkelvoudige versus de gecombineerde indicator voor bepaling van de fosfaattoestand van de bodem. Wageningen. https://doi.org/10.18174/557176

Debby Van Rotterdam, Nutrient Management Institute, Netherlands, presented results from 12-year field experiments “mining” phosphorus (P offtake in grass, no P fertilisation). Within a 75 ha stream watershed in Drenthe, The Netherlands, treatments with or without N and K fertilisation (in both cases, without P fertilisation) were tested on plots with different moisture conditions, and peat or sandy soil. Initial soil available P levels varied considerably, from 10 to 200 mgP$_{\text{-Al}}$/kg soil, with most samples in the range 40 - 90. Most samples are thus in the low range of agronomic recommendation (< 120 mgP$_{\text{-Al}}$/kg soil) but some are classified as too high compared to target levels for natural grassland (target level is <45 mgP$_{\text{-Al}}$/kg soil for species rich grassland).

P “mining” resulted in a reduction of soil available P (in soil 0 - 50 cm depth) in most plots (after 12 years), with the reduction rate linearly related to initial P$_{\text{-Al}}$. The reduction rate was c. 8.7 mgP-$_{\text{P-Al}}$/per year in soil with 200 mgP$_{\text{-Al}}$/kg.

In sandy soils, this decrease of available soil P was 2 – 7 times lower than P-offtake (in grass), whereas the decrease in total available soil P reserves (P$_{\text{-ox}}$ = oxalate extractable) was of the same order of magnitude as the P-offtake. P$_{\text{-Al}}$ and P$_{\text{-ox}}$ decreased considerably less in peat soil and in wet soils compared to sandy soils, despite similar levels of P offtake in grass.

Grass crop yields and P-offtake in grass were on average reduced by 50% with no N and K fertiliser. **As soil phosphorus levels were reduced over time, the differences between NK and no-NK plots decreased**.

In each individual plot grass crop yields did not significantly decrease over the 10 years, despite no P fertilisation, but P-offtake in the grass (P content) did decrease (by on average around 35 %).

“Natuurontwikkeling Roeghoorn; Resultaten van 10 jaar uitmijnen en verschralen in het beekdal van het Oostervoortschediep”, Van Rotterdam D, R. Postma, M van Doorn 2021, Nutriënten Management Instituut BV, Wageningen, Rapport 1802.N.21, pp 45 LINK.

Sabina Braun, Swedish University for Agricultural Sciences, Sweden, presented long-term field trials ongoing at nine sites across Sweden since 1957-1966, with two crop rotations. At each site, soil P is monitored (P_{-AL} ammonium acetate lactate P) and plots are tested with four levels of N application and four levels of P+K application (zero, balanced = replace offtake, and two levels of net fertiliser application).

Initial soil P_{-AL} levels ranged between 2 and 14 mg P kg^{-1} soil, and was lower than current agronomic recommendations at three sites, and in line with or higher than recommended levels at six sites.

Balanced P fertilisation often led to a small decline in soil P_{-AL} (-0 to -40 mg P/kg soil).

Crop yields show high variation between sites and between years, resulting in no overall statistically significant difference between above balance PK fertilisation and balanced PK fertilisation. However, there were differences in some years: **PK fertilisation above balanced brings higher yield only in good years (weather).**

All levels of PK fertilisation (balanced, low, high) showed higher yield than no-PK plots in most years for the first 30 years, and for all years since around 1990 (500 – 2000 kg grain / ha higher yield since around 1990).

Amy Shober and Nicole Fiorellino, University of Delaware, USA, presented long-term field trials on three farms in Maryland, ongoing since 1994. Fields were fertilised with poultry or dairy manure for four years, 1994 to 1997, applying 0 – 1600 kgP/ha/y, then no further P fertiliser was added in the following years. The manure application caused soil Mehlich P to increase from 50 to c. 350 ppm (depending on the manure loading applied). Results show that the 50 ppm Mehlich P is the agronomic target value: low limit to avoid risk of crop yield loss with little increase in crop yield at soil P levels higher than this.

‘Draw-down’ of soil phosphorus P since 1997, by cropping without any phosphorus application, resulted in a **decline in soil P in the plots not having received manure, down to around half the target 50 ppm Mehlich.** Around ten years of draw-down brought the soil P levels back down to 50 for the plots having received the lowest manure loading (400 kgP/ha/y x 5 years) whereas the plots having received the highest loading are not estimated to return to soil P 50 until after maybe 40 years of draw-down.

Crop yields were higher in the fields having received manure, compared to no manure, even through to 2022.

“Long-Term Agronomic Drawdown of Soil Phosphorus in Mid-Atlantic Coastal Plain Soils”, N. Fiorellino et al., Agronomy Journal, Volume109, Issue2, March–April 2017, Pages 455-461 *https://doi.org/10.2134/agronj2016.07.0409*

“Is Starter Phosphorus Fertilizer Necessary for Corn Grown on Atlantic Coastal Plain Soils?”, N. Fiorellino et al., 2021. Agrosystems, Geosciences & Environment. 4: 1−8. *https://doi.org/10.1002/agg2.20139*

“The challenges of managing legacy phosphorus losses from manure impacted agricultural soils”, Z. Qin & A. Shober. 2018, Current Pollution Reports 4:265-276. https://doi.org/10.1007/s40726-018-0100-1

Emileigh Lucas, University of Maryland, USA presented data from the 15-year drawdown period for long-term field trials on three farms in Maryland. Three sites received dairy or poultry manure for four years, with total P application of 0 to 1600 kg /ha, then no further P was added. The goal of this research was to determine agronomic and environmental P levels decline 15 years after no P application. Data showed that above 0.15 PSI (Phosphorus Saturation Index, see Lexicon), the slope between PSI and WEP (Water Extractable Phosphorus) became steeper, suggesting a greater loss of WEP with an increase in PSI. PSI of 0.15 was thus identified as a threshold to limit environmental risk of P loss.

Even fifteen years after application of manure, fields having received more than 200 kg P/ha/y still showed PSI higher than this environmental threshold, suggesting long-term risk of P loss from legacy P soils.

200 kgP/ha is comparable to the application rate of poultry litter to corn if based only on N, but largely exceeds [Maryland agronomic recommendations]() for P application..

The soil P storage capacity (SPSC) equation, which uses PSI to determine estimated availability of P to crops indicated that fields receiving more than 200 kg P/ha/y for four years **will act as a source of P to crops 15 years after P applications ceased**.

Data also showed that the WEP for fields having received 400 kg P/ha/y for four years exceeded a regional environmental threshold of 8.6 mg/kg 15 years after P applications ceased.

Other local data (Roswall et al. 2021) from other fields with Mehlich P of 500 – 1100 mg/kg, which is very high soil P, found **that soil WEP pool will continue to be available above US EPA environmental threshold level** after eight sequential extractions at 1:100 soil to water ratio.

These studies show that fields with high excess phosphorus application as manure, resulting in very high soil P, a likely to be a source of environmental P losses for decades.

Lucas, E., G.S. Toor, & J. McGrath. 2021. Agronomic and environmental phosphorus decline in coastal plain soils after cessation of manure application. Agriculture, Ecosystems & Environment, 311, 107337. https://doi.org/10.1016/j.agee.2021.107337

Roswall, T., E. Lucas, Y. Yang, C. Burgis, Isis SPC Scott, & G.S. Toor. 2021. Hotspots of legacy phosphorus in agricultural landscapes: Revisiting water-extractable phosphorus pools in soils. Water, 13, 1006. https://doi.org/10.3390/w13081006

Tiequan Zhang, Harrow Research and Development Centre, Agriculture and Agi-Food Canada, showed results of 14-year field trials in Ontario, Canada. At one site with initial high soil P (Olsen-P > 60 mg/kg), draw-down (corn-soybean rotated cropping, no P fertiliser) caused Olsen-P to fall to around 30 mg/kg without loss of crop yield. In another plot, with initial soil P around 30, fertiliser application of 50 kgP/ha/y resulted in Olsen-P staying fairly stable around the initial value. Crop yield for this plot was similar to that of the draw-down plot. In both cases, corn yield showed wide variations between years (reaching three times higher in some years than in most years) whereas soybean yield remained fairly constant between years.

In-field year-round water monitoring systems (surface run-off and tile drainage) showed **higher P losses from the fertilised plot (over seven years) despite this plot having lower soil P**. Most of this higher loss was particulate P, suggesting that this result may be due to tile drainage in the fertilised plot, leading to preferential flow.

These results suggest that **soil Olsen-P > 30, at this site, does not increase crop yield**. The higher P losses to water from the fertilised plot compared to the draw-down plot, despite lower Olsen-P, justify verification to establish whether this is due to specific conditions of the plots studied (e.g. drainage) or because losses are different from freshly applied P compared to soil-accumulated P

See also Zhang et al. in Frontiers in Earth Science. 2020 summarised in [ESPP eNews n°56]().

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Barbara Cade-Menun, Agriculture and Agri-Food Canada, presented long-term trials since 1967 at Swift Current, Saskatchewan, Canada. Plots were treated with different combinations of phosphorus and/or nitrogen, with analysis of soil and crop.

Results show that that **P fertilisation at 10 kgP/ha/y increases soil total P and soil Olsen-P, especially if P is fertilised but not N.**

Olsen-P varied from 9 to 44 kg/ha depending on fertilisation and crop system, with agronomic recommended levels being 30 kg/ha or lower for a crop response to P fertilisation.

Plots not receiving P fertiliser showed statistically significantly lower yields only for continuous wheat with N fertiliser. Both grain yields and grain P content averaged over ten years were also somewhat lower (average c. -10%) for all other systems, comparing without and with P fertiliser. **However, for most years there were no differences in yield or grain P between treatments with N and P and treatments with N only.**

N fertilisation impacted yields more than P fertilisation, as did levels of precipitation (in this non-irrigated system). The plots were not limed, and long-term N application led to soil pH decrease (from c. 7 to c. 5.5). This decreased exchangeable Ca and Mg and increased exchangeable Al and Fe, altering P cycling and microbial activity.

"Investigation of soil legacy phosphorus transformations in long-term agricultural fields using sequential fractionation", J. Liu, Y.F. Hu, J.J. Yang, D. Abdi and B.J. Cade-Menun. 2015, P K-edge XANES and solution P-NMR spectroscopy. Environ. Sci. Technol. 49:168-176 https://doi.org/10.1021/es504420n

"Long-term effects of nitrogen and phosphorus fertilization on soil microbial community structure and function under continuous wheat production on the Canadian prairie", Y. Li, J. Tremblay, L. Bainard, B. Cade-Menun, and C. Hamel. 2020.. Environ. Microbiol. 22:1066-1088 https://doi.org/10.1111/1462-2920.14824

"The influence of long-term N and P fertilization on soil P forms in a wheat/fallow cropping system", S. Chen, B.J. Cade-Menun, L.D. Bainard, M. St. Luce, Y. Hu, and Q. Chen. 2021.. Geoderma 404:115274 https://doi.org/10.1016/j.geoderma.2021.115274

Soil phosphorus and losses to rivers

Sarah Stackpoole, US Geological Survey, indicated that agricultural P surpluses are widespread across the USA. P balances from 1992 to 2012 indicated P surplus in 117 watersheds, balances in 44, and deficits in 12. However, analysis of the watersheds suggests **no relationship between changes in phosphorus balance and river P loads**.

For example, in 44 watersheds, river P loads increased despite reductions in agricultural P balance. However, only 8 of these showed that legacy P contributed to river P loads. Despite the decreasing trends in the P balances between 1992 and 2012, many watersheds continued to have P surpluses. Therefore, the disconnect between agricultural P balance and changes in river P load may have resulted from the influence of latent processes, including an exceedance of the watershed buffering capacity, or from changes in agricultural management practices.

A second study on the Mississippi River Basin covered 1950 to 2017, over which time agricultural nutrient balances for both P and N remained always positive (surplus) with average balances over the total period of c. 3.3 kgP/ha/y and c. 13.6 kgN/ha/y. From 1950 to 1975, nutrient surpluses increased annually, whereas after 1975, N balances varied around a slow annual increase and P balances fell 1975 – 1985 then varied around a slow annual increase. River N and P balances increased until around 1985, and after that were not correlated to agricultural P balances. The authors conclude that latent factors , which may include management practices or changes in watershed buffering capacity ,were just as important as agricultural nutrient balances for explaining river nutrient load changes for N and even more important for P.

"Variable impacts of contemporary versus legacy agricultural phosphorus on US river water quality", S. Stackpoole et al., Proceedings of the National Academy of Sciences 116:20562-20567, 2019 https://doi.org/10.1073/pnas.1903226116

"Long-Term Mississippi River Trends Expose Shifts in the River Load Response to Watershed Nutrient Balances Between 1975 and 2017", S. Stackpoole et al., Water Resources Research, 57(11), e2021WR030318, 2021 https://doi.org/10.1029/2021WR030318

Juliane Hirte, Agroscope, Switzerland, modelling of transport of agricultural P into Lake Baldegg, Switzerland, using a rainfall-runoff-P model with information on the hydrological behaviour of soils, measured soil test P-CO_2 data (CO_2-saturated water extraction), and a P decline function based on pot experiments to estimate P losses. Soil test P values in the lake catchment averaged 2.5 mg P-CO_2/kg.

A target of 1.6 mg P/kg soil P-CO_2 was estimated as sufficient to reduce P inputs to Lake Baldegg by 50%. The authors indicate that this is in the range of Swiss agronomic recommendations (based on Flisch et al. 2017). It represents however a reduction of 1/3 in average soil P in the catchment.

The 24-week P-mining pot experiment generated data on decline in soil P with ryegrass and three fertilisation levels, including zero fertilisation.

Using this data, **modelling estimated that it would take 2 – 9 years to bring soil P levels down to a target level** of 1.6 mg P-CO_2/kg if P fertilisation was stopped in the catchment, but NK fertilisation continued, or 8 – 32 years if NPK fertilisation was entirely stopped.

"The time it takes to reduce soil legacy phosphorus to a tolerable level for surface waters: What we learn from a case study in the catchment of Lake Baldegg, Switzerland", C. Von Arb et al., Geoderma 403 (2021) 115257 https://doi.org/10.1016/j.geoderma.2021.115257

Discussion noted the very variable results between different trials, and also within trials between plots or years. A challenge is that the sites which give the most visible results are those which respond to fertiliser application, and these tend to be sites with poor soil quality and low fertility.

Understanding trial results requires looking not only at soil plant available P, but also at soil P stocks and P binding capacity of soil, because these drive availability of P to crops. Also, as shown above, P in soil below the surface layer can be an important resource for crops. These factors need to be taken into account in agronomic recommendations.

Field tests of "P mining" and soil phosphorus

Agnieszka Rutkowska, State Research Institute for Soil Science and Plant Cultivation, Poland, explained that P fertiliser application recommendations in Poland depend on soil P status, recommending balanced fertilisation (P addition = P offtake) when soil P is 100 - 200 ppm P_2O_5 soil (Egner Riehm Domingo), with zero P fertilisation recommended above soil P 40. Soil P is generally in the 10 – 20 target range in much of Poland, but lower in one region and higher in four regions.

Dr. Rutkowska presented results of **16-year field experiments at two sites (Grabów, East Poland and Baborówko, West Poland),** sandy soils pH 6.2 and 6.8, under crop rotation (winter rape, winter wheat, maize, spring barley), with and without (mineral) P fertilisation, and with varying levels of (mineral) N fertilisation. Both sites had very high initial soil phosphorus (70 and 116 ppm P_2O_5/soil) resulting from historic mineral fertiliser application.

At Grabów, with high initial soil P, soil P was considerably increased after 16 years on plots where P fertiliser was applied but N was not, but did not significantly change where both P and N were applied. When no P was applied, but also no N, soil P was not significantly changed, but with no-P and N application, soil P was reduced by around 30% after 16 years.

At Baborówko, with even higher initial soil P, application of P fertiliser led to a c. 30% increase in soil P after 16 years, whereas no-P did not significantly reduce soil P. N fertilisation did not significantly impact these results.

"Productive and Environmental Consequences of Sixteen Years of Unbalanced Fertilization with Nitrogen and Phosphorus—Trials in Poland with Oilseed Rape, Wheat, Maize and Barley", A. Rutkowska & Skowron, Agronomy 2020, 10, 1747; https://doi.org/10.3390/agronomy10111747

Yu Gu, Wageningen University Research, Netherlands, presented long-term field trials at Qiyang, Hunan Province, China. Trials are underway since 1990 with winter wheat – summer maize cropping, and several different NPK mineral fertiliser treatments, manure treatment and no fertiliser. Initial soil phosphorus was 14 ppm Olsen-P.

Results show that soil soluble phosphorus ($CaCl_2$) increases with surplus application (higher than offtake) but that reactive P pools were saturated at high P surplus applications (oxalate P and Olsen-P ceased to increase with further P application).

PSI (Phosphorus Saturation Index, see Lexicon) showed to be a good indicator or risks for both crop yield and phosphorus losses to surface waters, with **thresholds of PSI = 0.25 as minimum to ensure crop productivity but PSI = 0.135 as a level above which risk of P losses increases rapidly with P application**.

Andrew Margenot and Maia Rothman, University of Illinois, USA, presented two long-term field trials in the US Illinois corn belt, Morrow, 145 years and Monmouth, 37 years.

From the second World War until 1990, phosphorus accumulation in Illinois was estimated at 2 million tonnes P (fertiliser applied minus offtake and losses). This is c. 4% of total P in Illinois soils and around 10% world annual phosphate rock mined (see ESPP Factsheet).

At Monmouth, pig manure was largely applied until 1980 and since only one single initial application of 45 kgP/ha fertiliser was made, with cropping of maize and soy then removing a total of nearly 1 tonne P/ha over 37 years. Soil Mehlich P shows wide variation between years, but has overall declined from around 60 to around 20 ppm. However, only around one third of the 1980 total soil P stock is considered to have been mined. Crop yields were unaffected by the P drawdown, consistent with soil P results.

The Morrow site has stored soil samples over 145 years, with detailed records of fertiliser inputs and crop offtakes. Analysis shows that accumulated soil P (top 30 cm of soil) is much higher than suggested by Mehlich P levels. Fertilised plots today have Mehlich P c. 90 ppm, which calculates to just over 200 kgP/ha, whereas the P-budget estimates c. 4 000 kgP/ha and soil P analysis indicates 300 kgP/ha.

In plots which are cropped but have not been fertilised since 1876, Mehlich P has declined to c. 30 ppm. **Depending on crop rotation, maize grain yields in year 145 for unfertilised plots ranged 1.3 - 7.7 t/ha and for fertilised plots ranged 15.4 - 18.2 t/ha**.

Phosphorus traps and management practices

Paulo Pavinato, University of Sao Paulo, Brazil, estimated that 33 million tonnes of phosphorus had been accumulated in Brazil's soils in the five decades to 2016, with a mean Phosphorus Use Efficiency (P in crop/P in fertiliser) in current intensive agriculture of 72% for maize, 50% for soy, 31% for sugarcane and 3% only for coffee.

He presented pot trial results using the forage cover crops *Urochloa ruziziensis* (brachiaria) as a phosphorus trap. After 12 monthly cuts of brachiaria **significant reductions in soil total P were observed, in particular in soil inorganic P**, and more notably in sandy soils.

Brachiaria can be grazed or harvested forage material.

"Revealing soil legacy phosphorus to promote sustainable agriculture in Brazil", P. Pavinato et al., Nature Scientific Reports, 2020, 10:15615 https://doi.org/10.1038/s41598-020-72302-1

Victoria Barcala, Deltares, The Netherlands, presented farm-scale studies at Huppel, The Netherlands (sandy soil), monitoring P in soils and in the farm drainage ditch. See SCOPE Newsletter n°138. The site has high soil phosphorus (450 – 1 600 WEP mg/kg (water extractable P), compared to a background level of around 350 WEP resulting from historic high manure application rates (P surplus 30-50 kgP/ha in the 1970's and 1980's, reduced to 10-20 kgP/ha by 2010).

The sandy soil allows rapid transport of phosphorus to the drainage ditch, via subsurface flow and tile drains. In the ditch, much of the P reacts with iron, and P in the ditch outflow is mostly particulate. **Total P discharge from the drain in 2018-2019 was 0.4 kgP/ha, so much lower than the historic P surpluses**.

Weirs are being tested in the ditch to try to retain phosphorus in sediment and prevent losses to surface waters downstream. However, this has raised the water table, so resulting in increased P release in soils by transport nearer the surface without reaching the deeper iron-rich soil layers.

"Processes controlling the flux of legacy phosphorus to surface waters at the farm scale", V. Barcala et al., Environ. Res. Lett. 16 (2021) 015003 https://doi.org/10.1088/1748-9326/abcdd4

Vladimir Nosov, PhosAgro, Russia, presented field trial data from Lithuania, using winter rapeseed, showing that effectiveness of phosphorus applied in fertiliser depends on the form of fertiliser used and the mode of application. The soil was sandy loam, with pH 6 – 6.2 and a good level of phosphorus (210 -230 g ppm P_2O_5/soil) due to historical fertiliser application.

Results show that, in these conditions, replacing a dry mineral fertiliser by **liquid ammonium polyphosphate enabled to increase yield** whilst decreasing P application, with further yield increases possible by split application (before planting and then foliar application in spring). Taking into account crop yield, fertiliser costs and application costs, these brought economic benefits for the farmer.

The P fixation in soil may be lower, and so better plant availability, because of the neutral pH of ammonium polyphosphate.

Discussion

Need to update agronomic recommendations

Several speakers and panellists underlined the need to update fertiliser recommendations to farmers. Crop yield potential and Phosphorus Use Efficiencies have evolved but **soil P status classes, crop P removal coefficients and fertiliser application recommendations have often not been updated** for decades. Recommendations also need to be adapted locally.

This is important both to improve environmental protection by avoiding over application of phosphorus, but also to ensure crop productivity, as in a number of regions it is now seen that P-balances are negative.

The concept of "Subsoil P Supply Power", still used in some US Midwest States (see e.g. Illinois Agronomy Handbook, in chapter 8), should maybe be updated to take into account potential for crops of Legacy P. See A. Margenot here.

Recommendations concerning conservation measures, such as phosphorus retention in vegetation buffer strips or stream or drain P-traps, also need to be updated. Such installations require monitoring and management over time.

It is also questioned whether a system of **regulatory limits on P fertilisation across Europe** would not be an effective tool to prevent over-fertilisation and so to limit P-losses and eutrophication. This would raise awareness of phosphorus losses and eutrophication. Such limits, or balanced fertilisation requirements, exist in a few countries and regions only today – see D'Haene & Hofman, below.

Crops need to be more P efficient

Key challenges identified are that the threshold to limit P losses is generally considerably lower than soil P levels sufficient to ensure optimal crop yield. Soil P in the range between these two thresholds is not easily available to plants.

Techniques need to be developed to improve crop P uptake, so that they take up less available, soil-bound P (Legacy P) and not only soluble P. Such techniques include plant breeding, biostimulants, new fertiliser products, but require a holistic approach, not one single solution.

Participants pointed to papers showing that, under controlled environmental conditions, mycorrhizal fungi and bacteria can facilitate P uptake in maize (Battini, et al. 2017) and in barley (Ibáñez et al. 2021). However, under more complex, field-like conditions, associations with P solubilising microbes often fail to produce positive outcomes (Raymond et al. 2021) which indicates that a more mechanistic understanding of the plant-microbe-soil interaction is needed in order to harness positive effects P solubilising microbes in the field (for an example of the complex interaction between arbuscular mycorrhiza and P solubilising microbes see Jiang et al. 2021).

Importance and challenges of soil P testing

To optimise nutrient application, farmers need to know how much phosphorus is stored in soil, in what form, whether it is plant available and to what extent it is likely to leach. **Soil P testing is therefore an essential part of agronomic fertiliser recommendations**.

However, the widely used soil tests (such as Olsen-P) do not fully reflect reality. This results in often wide ranges for agronomic recommendations (e.g. Olsen-P 8 to 40 ppm). **Better P extraction tests are needed** to assess different forms and availability of soil P.

See however Sims et al. 2016 which shows reliable prediction by Mehlich P of Water Extractable P.

A major challenge is how to implement soil P testing on the farm: how many tests are economically and operationally feasible? Where in the field? When?

Different soil P tests are used in different countries making comparison of agronomic and scientific data difficult.

Data and long-term trials

Panellists agreed that **better knowledge of Legacy P needs to be developed** to support advice to farmers, environmental management, mitigation measures. More data is also needed to improve models:

- In what forms is Legacy P held in soil?
- In which soil layers?
- In which parts of the field?
- How is Legacy P released by plants?
- When is Legacy P soil leached?
- How is it transported and to where?

Long-term field trials are very important, because soil phosphorus storage, plant uptake and environmental loss are processes over decades. Long-term field trials are particularly important to better understand how crop yields are likely to be impacted if P inputs are reduced.

When and how fertiliser is applied is also very important. See for example Roth et al. 2011 DOI, who show that even on high-P soil (according to soil P tests), starter P fertiliser application can significantly increase yield of maize.

Valkama et al. 2009 DOI, in a meta-analysis of 80 years of research in Finland, showed that P fertilisation increased crop yields by average 11% compared to n-P (but N and K) fertilisation. Results varied between soil types. On some high-P soils (P_{AC} > 10 mg/l) yield response to P fertilisation was negligible, but on clay soils yield increased with P fertilisation even on high P soils. **Overall, the P fertilisation rates justified by the meta-analysis (for perennial grass and cereals) were only around half the maximum values allowed** by the Finnish Agri-Environmental Program or those applied in practice on many farms.

What about Legacy N

The **link between N and P** was underlined by several participants: the Redfield ratio and stoichiometric balance in bio-geological cycles. See Peñuelas & Sardans, 2022 DOI)

N will often not be stored in soils, because of leaching of nitrates or loss to the atmosphere, but results presented by several speakers show that N fertiliser application considerably modifies crop use of Legacy P.

Communication

Several panellists underlined the difficulties of communication between science, industry, regulators and farmers.

A **shared vocabulary** is lacking. Soil P can refer to different and non-comparable test methods. There is no shared definition of "Legacy Phosphorus" (see discussion above).

How can knowledge on Legacy P be **scaled up** to communicate to farmers and to integrate into regulatory frameworks, such as Common Agricultural Policy funding?

How to manage expectations over time? As shown in several presentations, agricultural management measures will not prevent P losses from historically over-fertilised soils until decades into the future. Mitigation systems installed on farms, such as buffer vegetation is not "for ever" and may need renewing after a number of years.

What is a "significant" reduction to crop yield

The point of view of farmers or scientists to given data can be very different. **Scientists will conclude, correctly, that crop yields are not "statistically lower" in trials with no P fertiliser, but the farmer will see yields maybe 5 – 10% lower. However, such a difference could represent a substantial difference in take-home margin for the farmer**.

As shown by Sabina Braun, above, application of P fertiliser did not "statistically significantly" increase yield on average over all years, but did so in some good weather years.

Jakob Magid (Chat) noted that in field trials in Denmark, yield was higher in 'bad' (cold) years in no-P plots, but no effect in 'good years' (Van der Bom, Magid, Stoumann Jensen, 2017, summarised below).

Studies cited by **Kari Ylivainio** also show that low temperatures or waterlogging can reduce crop P uptake, so compensation by increased fertiliser application will result in increases in soil P stocks and in potentially leachable soil P (Ylivainio & Peltovuori 2012, Ylivainio, Jauhiainen, Uusitalo & Turtola 2017).

Does the farmer estimate it worth the additional fertiliser cost every year to profit from the higher yield in some years?

Furthermore, as several presentations showed, **the agronomic optimal level of soil P is significantly higher than thresholds estimated to limit P losses, and so prevent eutrophication**.

Overall the question is therefore posed of what degree of yield loss is acceptable to society to ensure environmental protection? And where? And how to implement this: regulation? agri-environment funding.

Summaries of published studies

No coherent phosphorus legislation in Europe

D'Haene & Hofman, in two 2021 papers, summarise status of agricultural phosphorus limitation regulations in Europe and possible implications for soil organic matter (SOM).

Information on phosphorus application limits was collected for twenty Member States and regions in Europe, showing wide disparities, and no regulatory limits in more than one third (7/20).

There is a slow increase in the number of states and regions with such limits: **four countries have introduced P-application limits since previous studies in 2014 (**Amery & Schoumans) and 2007 (Schoumans).

In many cases, limits depend on soil P status, with soil P classes defined in legislation. The definitions are however widely different across states and regions: for example, the number of soil classes varies from 3 to 10. In many cases, soil P classes do not take account of soil characteristics.

In most states and regions with P application limits, soil testing is obligatory, but the number of samples, frequency and other requirements vary widely. In some cases, soil testing is only required in fields under AEP (Agro-Environmental Programme). Also, the P soil test methods used are different including: Olsen-P, acid ammonium citrate, ammonium lactate, calcium-acetate-lactate, double lactate, electro-ultrafiltration, Morgan's, Mehlich and water extraction.

In around half of the states and regions with P application limits, these differ depending on the crop.

In most of the states and regions with P application limits, these apply both mineral P fertilisers and P in organic amendments (esp. manure), but in Estonia and Hungary limits apply only to manure, in Northern Ireland only to mineral fertilisers, and in Sweden only to manure if soils are below optimal levels. The authors suggest that where soil P status is above target levels, P application limits should be lower than P offtake in crops, in order to bring down soil P levels.

"Does legislation mitigate the impact of legacy soil phosphorus on water quality in horticultural fields?", K. D'Haene, & G. Hofman, Acta Hortic. 1327. ISHS 2021. https://doi.org/10.17660/ActaHortic.2021.1327.107

Interactions with Soil Organic Matter (SOM)

Soils with high SOM are known to enable optimal crop yield at lower levels of plant available phosphorus, because P bonding to organics is low-energy. This poses questions in that limiting manure and slurry application can lead to lower soil SOM as well as reducing P application.

Also root and tuber crops, and horticulture (vegetables, flowers) result in lower return of plant organic matter to soil. Such crops also have a less developed root system, so rely more on soil structure and SOM for healthy development.

The authors conclude that, as states and regions introduce **P application limits, this may negatively impact soil organic matter levels**. Legislation should take this into account by fixing limits dependent on soil P status and on crop (and so expected P offtake), lower P-application limits for soils with high SOM, and by targeting limits to sensitive catchments.

"The trade-off between the reduction of phosphorus losses and the maintenance of soil quality in legislation", K. D'Haene, & G. Hofman, Acta Hortic. 1327. ISHS 2021. https://doi.org/10.17660/ActaHortic.2021.1327.26

Estimating P offtake in Europe

An assessment by authors from the European Commission and the University of Pavia, Italy, concludes that phosphorus offtake from agricultural land in Europe totals c. 2.6 million tonnes P/y (± 9% uncertainty), of which 94% in crops and 6% in crop residues removed from fields.

2.6 MtP/y is 11 – 15% of total world phosphate rock production (see ESPP Factsheet).

The largest P removal is in cereals (38% of P offtake, 32% of agricultural land), grass (33% of offtake, 33% of land) and fodder crops (12% of offtake).

The study also discusses soil available phosphorus, suggesting based on literature, that the critical threshold from crop production is around 18 -25 ppm Olsen-P and the optimal level 25 – 50 ppm Olsen-P. Around 13% of land in the EU+UK has soil P higher than this optimal range, whereas 28% shows a P-deficit. (*ESPP comment: the 28% includes areas such as mountains, dry areas, etc where inherently low agricultural productivity may not justify higher soil P*). The map of soil P levels across EU+UK from Ballabio et al. 2019 is shown (see ESPP eNews n°40)

The study estimates P offtake for 220 regions in the EU (plus UK), by combining data on crop areas Common Agricultural Policy data (CAPRI 2016), crop production rates (CAPRI compared with Eurostat and Crop Growth Monitoring System CGMS – MARS), crop moisture content (Eurostat) and P content of different crops (34 crops, data from tables of composition and nutritional value or other publications).

The EU+UK mean P offtake rate is c. 14 kgP/ha/y. The highest P offtakes are in Ireland, The Netherlands, Belgium and Denmark (>19 kgP/ha/y). Offtake rates are lower than 10 kgP/ha/y in Mediterranean and South-East Europe countries.

The three countries with the highest agricultural production (Germany, France and the UK), which together cover c. 1/3 of Europe's agricultural land, account for nearly 50% of total P offtake.

The highest P offtake intensities are for tomatoes, flowers and other vegetables (at 40 – 50 kgP/ha/y), followed by sugar beet (c. 25 kgP/ha/y).

Predicted scenarios for agricultural production to 2030 will lead to an increase in total P offtake of +4%.

"Phosphorus plant removal from European agricultural land", P. Panagos et al., Journal of Consumer Protection and Food Safety 2022 https://doi.org/10.1007/s00003-022-01363-3

Data are available here: https://esdac.jrc.ec.europa.eu/content/phosphorus-plant-removal

Estimating P fertiliser demand for China

Modelling based on long-term field trial data suggests that phosphate fertiliser demand in China (2013 -2080) would be reduced be around half by stopping P-fertiliser application in counties with high Olsen-P then moving to balanced fertilization.

The modelling uses data from six long-term field fertiliser experiments, running since 1980 in Jinxian and since 1990 in Yangling, Chongqing, Zhengzhou, Gongzhuling, and Qiyang. For each of these sites, a "plateau" Olsen-P – yield response curve was assumed, with linearly increasing yield up to a certain critical Olsen-P level, but then no yield response for higher Olsen-P. See e.g. Bai, 2013, as referenced for detailed results for three sites. **This is the Olsen-P – yield "breakpoint"** described by Johnny Johnson in SCOPE Newsletter n°98 (October 2013).

This breakpoint, above which no further crop yield is assumed to result, was indicated by Bai to range from 11 to 21 mg/kg. Bai indicates that above this, crop yield will respond less, and does not indicate zero crop response. Table S1of the Yu 2021 paper indicates Olsen-P breakpoints of 8 – 30, depending on crop and trial site.

For simplification, the modelling is however based on breakpoints of 20 mg/kg Olsen-P in Northwest China, 15 mg/kg in North Northeast China and the Yangtze Plain, and 35 mg/kg in South China. **The model then assumes zero increase in crop production above these levels**.

The model estimates P takeoff in harvested crops, P-losses to water (0.4 – 1.3 kgP/ha/y for different regions) and P-supply from weathering (1 kgP/ha/y) and atmospheric deposition (0.25 kgP/ha/y). The model then calculates fertiliser use in different scenarios, based on fertiliser or manure input to bring average Olsen-P in counties with current low soil P up to the breakpoint, and on reduced fertiliser input to allow average soil P to descend down to the breakpoint in counties with current high soil P.

The modelled scenarios suggest that China's total P fertiliser consumption could be reduced by around half, compared to c. 11 MtP/y total (average per year, 2013-2080) based on current trends. No estimate is made of yield gain or loss from the P fertiliser reduction strategies.

"Estimation of the P Fertilizer Demand of China Using the LePA Model", W. Yu et al., Front. Environ. Sci., Front. Environ. Sci. 9:759984, 2021 https://doi.org/10.3389/fenvs.2021.759984

"The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types", Z. Bai et al., Plant Soil (2013) 372:27–37 https://link.springer.com/article/10.1007/s11104-013-1696-y

Legacy P in Xinjiang, China

Over 30 years of fertiliser application shows to have only slightly increased total soil phosphorus, but to have multiplied Olsen-P by 3.6x. Extractable P was related to soil organic carbon, nitrogen and carbonate. The authors suggest that the labile legacy P can be crop available so reducing the need for new fertiliser application.

Data was analysed from 1981 to 2013, for 204 sites in the Xinjiang region, North West China, in over 500 publications. Other data showed that average P application to cropland over this period was 23 kgP/ha/y. Compared to crop offtake, this would result in a "Legacy P" accumulation of 135 kgP/ha.

Also, soil samples were analysed in calcareous soils in adjacent fertilised cropland and uncultivated land at 15 sites in the Shihezi region, Xinjiang.

Over the period, total soil P increased by <10% in fertiliser cropland, but average Olsen-P increased from 7 to 26 (3.6x increase). Total P was 16% higher in cropland (0 – 30 cm) compared to uncultivated land, whereas Olsen-P was nearly twice as high.

In cropland, sodium bicarbonate extractable P was positively correlated to SOC (soil organic carbon), calcium carbonate and total nitrogen, whereas in uncultivated land there was no correlation.

The authors conclude that the **labile and moderately labile phosphorus present after prolonged fertiliser application** represents 'Legacy P' which can be a source of phosphorus to crops, so reducing need for fertiliser application.

"Legacy phosphorus in calcareous soil under 33 years of P fertilizer application: Implications for efficient P management in agriculture", L. Zhang, J. Chen, G. Chu, Soil Use Manage. 2022;00:1–14, https://doi.org/10.1111/sum.12792

Importance of landscape for Legacy P release

A water basin study (134 km^2, headwaters of the Xiangjiang River) shows that landscape and land use considerably modulate release of Legacy P. Woodland and ponds reduce Legacy P release whereas cropland and urbanisation increase Legacy P release.

The catchment has a majority of woodland landcover, with intensive cropland, tea plantations, villages, ponds and household pig breeding.

Water samples were collected at 8 sites on different headwaters, three times per month, for six years. Average Olsen-P for the 8 catchments varied from 7 to 14 mgP/kg and NAPI (net anthropogenic P input) from 7 – 31 kgP/ha/y, with a significant reduction in NAPI over the six year study period.

Analysis suggests that 51 – 83 % of river P$_{\text{-total}}$ export from the catchment was from Legacy P (phosphorus accumulated due to past NAPI), and 43 – 82% of dissolved river P exports (DIP).

Land use was identified to significantly modulate legacy P release with landscape configuration the most important factor, then landscape composition, both more important than terrain factors or soil type.

The authors note that this shows the importance of landscape planning for Legacy P management.

"Landscape patterns of catchment and land-use regulate legacy phosphorus releases in subtropical mixed agricultural and woodland catchments", C. Meng et al., Science of the Total Environment 804 (2022) 150055 https://doi.org/10.1016/j.scitotenv.2021.150055

Modelling Legacy P in France

Modelling based on data for inputs (fertilisers, manures, other), data for crop harvests and modelling of erosion P losses, suggests that much of France's cropland and grasslands have a negative P balance since around 2000, with only intensive livestock regions showing a positive balance.

GRAFS and DPPs models are used with data on soil P pools before 1850 and data on different P inputs and crop outputs (UNIFA, French national agricultural statistics).

Total P in agricultural soils is estimated to have increased by c. 24% in cropland (1850 to 2015), i.e. "Legacy P", but to have been depleted by c. 8% in grasslands.

It should be considered that soil P content had been depleted in France and much of Europe by 1850, as a result of food production and grazing to feed the population, without adequate return of phosphorus to soil (see e.g. González de Molina 2015)

Since around 2000, most French regions show negative P balances, reaching average around -10 kgP/ha/y net depletion by 2015 in both cropland and grassland (fig. 2).

The authors estimate that some of the phosphorus accumulated in France’s soils by high P-fertiliser application in the second half of the twentieth century (‘Legacy P’) could be “mined” to support crop production, but that nonetheless an **average 60 000 tP/y fertiliser input (total for France, from 2016) would be needed to keep all regions above the minimum soil Olsen-P level for crop requirements**.

“The phosphorus legacy offers opportunities for agro-ecological transition (France 1850–2075)”, J. Le Noë et al., Environ. Res. Lett. 15 (2020) 064022 https://doi.org/10.1088/1748-9326/ab82cc

“Nutrient Balances and Management of Soil Fertility Prior to the Arrival of Chemical Fertilizers in Andalusia, Southern Spain”, González De Molina et al. 2015, Hum. Ecol. Rev. 21 23–48 https://doi.org/10.22459/HER.21.02.2015.02

Soil P, runoff and crop yield

P losses in rainwater and snowmelt and crop yield were compared for two periods: 1997-2005 before P-drawdown, approximately balanced P fertilisation ; and 2006-2014 P-drawdown, much lower (c. 40%) P fertilisation.

The trials used two fields in South Tobacco Creek watershed, Manitoba, Canada, which drains to Lake Winnipeg. Both fields were grown with common crops, i.e. spring wheat, canola, flax, barley and oats. The fields were tilled differently for the before P-drawdown period (one with conventional tillage and the other with reduced tillage), which resulted in different initial soil test P values at the start of P-drawdown (higher soil P in the low tillage field). Both fields were under conventional tillage during the P-drawdown period.

The reduced P fertilisation, providing 2-3x less P than in crop offtake, led to a downwards trend in soil Olsen P (0 – 15 cm depth) from 2007 – 2013, falling from around 15 to 10 in one field and from around 20 to 15 in the other field. Flow weighted total P concentrations in runoff were reduced by around 50% in both fields during the P-drawdown period, **but estimated total P losses per hectare were nearly unchanged in the field in which tillage method was unchanged** (conventional before P-drawdown, conventional during P-drawdown),. This may be the result of a greater runoff volume in the later study period. Total P losses per hectare were reduced in the field which changed from reduced to conventional tillage.

Crop yields were the same for canola in both fields and in both periods, but for wheat were nearly 50% higher in the second time period (but the same between the field with higher Olsen P and the field with lower Olsen P). **This suggests that in this case, the reduction of Olsen P (down to around 10) by phosphorus draw-down did not limit crop yield for these crops**.

In a second paper, the authors analysed edge-of-field phosphorus runoff and sediment data for 30 arable fields (total of 216 site-years) in Saskatchewan, Manitoba and Ontario, Canada, comparing with precipitation and soil P data. In all regions, precipitation (rainfall and snowmelt) quantities were correlated to total phosphorus losses, with snowmelt having the most impact. **In Manitoba, soluble P losses were strongly linked to Olsen-P in the top 0 – 5 cm of soil**, but this was not the case in Ontario where tile drainage accounted for most of water movement.

“Impacts of Soil Phosphorus Drawdown on Snowmelt and Rainfall Runoff Water Quality, J. Liu et al., J. Environ. Qual. 48:803–812 (2019) https://doi.org/10.2134/jeq2018.12.0437

“Phosphorus runoff from Canadian agricultural land: A cross-region synthesis of edge-of-field results”, Agricultural Water Management 255 (2021) 107030 https://doi.org/10.1016/j.agwat.2021.107030

Fertilisation, weather and crop yield

Long-term field trials in Denmark show considerably lower yields without fertilisation and that adequate nutrient availability is critical for ensuring stable, high yields despite climate variations.

This paper summarises results from the Long-Term Nutrient Depletion Trial (LTNDT) at Copenhagen University’s experimental farm, Taastrup, Denmark. From 1964, the experimental fields were continuously cropped with cereals with moderate N fertilisation but no phosphorus; then from 1996, seven different fertilisation treatments were installed: unfertilised, four combinations of mineral fertilisers (kg/ha/y : N at 60 or 120, P at 0, 10 or 20 and K at 0 or 60) and two levels of manure slurry. To assess the residual effects of these years of repeated treatments, in 2009, all fields were divided into plots with different levels of N mineral fertiliser (0 – 150 kgN/ha/y) and zero P, zero K.

After 13 years, soil Olsen P had decreased significantly in the unfertilised and zero-P fertilised fields (20 – 30% reduction). Nutrient balances (inputs in fertilisers minus offtake in grain yield x measured grain nutrient content) increased with fertiliser nutrient inputs.

Yields of spring barley (the main rotation crop) were significantly lower in the completely unfertilised field (18% to 75% lower) than in the field fertilised with NPK (at 60-10-

60 kg/ha/y each), and were also generally lower in the field fertilised with NK only (zero P).

Weather conditions significantly impacted yields between years, and yields were generally higher in years with higher Spring and Summer temperatures. Yield losses in years with low temperatures were higher in unfertilised fields.

Residual effects of the 13 years' different fertilisation treatments showed clearly in that the yield was lower in the fields having received no P fertiliser for 13 years (unfertilised, NK and zero P), for all levels of N fertiliser applied in 2009 (50 – 150 kg//ha) and was also amongst the lowest when no fertiliser was applied in 2009 (zero N).

The authors conclude that Spring barley yield and changes in soil Olsen P were correlated to phosphorus balance. Yield losses in cold years were accentuated by inadequate N or K fertilisation, and were partly attenuated by full fertilisation. **Accumulated soil P and K clearly improved grain yields with organic inputs (slurry) having a greater residual yield impact than mineral fertiliser**. The N use efficiency of applied mineral fertiliser was reduced by lower P and K availability remaining from previous applications of P or K.

"Long-term P and K fertilisation strategies and balances affect soil availability indices, crop yield depression risk and N use", F. van der Bom, J. Magid, L. Stoumann Jensen, Europ. J. Agronomy 86 (2017) 12–23 http://dx.doi.org/10.1016/j.eja.2017.02.006

Further studies from the same site:

"Long-term fertilisation form, level and duration affect the diversity, structure and functioning of soil microbial communities in the field.", F. van der Bom et al., Soil Biology & Biochemistry 122, 91–103, 2018 https://doi.org/10.1016/j.soilbio.2018.04.003

"Influence of long-term phosphorus fertilisation history on the availability and chemical nature of soil phosphorus.", F. van der Bom et al., Geoderma, 355, 113909, 2019 https://doi.org/10.1016/j.geoderma.2019.113909

Soil legacy P and soil organic carbon

Trials in fields with initially very high soil P in Belgium showed no crop yield loss when P fertiliser was not applied for four years (compared to P fertilised plots) and no reduction in soil P status.

The two trial sites in Flanders have sandy-loam soil and prior to the trials, the sites had been used for testing of crop protection products, with fertilisation according to limits under the Flanders Action Plan of the Nitrates Directive. Despite these limitations, both had initial very high soil phosphorus status (P_{Al} 0-30 cm = 460 – 530 mgP/kg, P saturation PSD 0 – 90 cm = 29 – 40 %). At both sites, P fertilisation to Flanders limits (as manure plus mineral fertiliser, that is 11 – 34 kgP/ha/y depending on crop and site) were compared to zero P (mineral N and K). Crop rotations included arable, rye-grass and vegetables.

P-balances (input minus offtake in crops) were negative (-6 to -9 kgP/ha/y), even for the P-fertilised plots, because Flanders fertiliser limits have evolved downwards. The negative P-balance was 3 to 5 times higher in the zero P plots.

After four years, soil $P_{\text{-CaCl2}}$ decreased in both P-fertilised and zero-P plots by -40 to -62%, $P_{\text{-Al}}$ decreased by -9%, whereas P soil saturation showed limited changes (-8 to +10 %). There were no significant differences in changes in soil P measurements between P-fertilised and zero-P plots.

Unsurprisingly, given the absence of impact on soil P status, there were no differences in crop yield between the P-fertilised and zero-P plots over the four-year trial.

Soil organic carbon (SOC) levels dropped during the four years, despite ploughing in of grass as part of the crop rotation. The fall in SOC was slightly smaller in the zero-P plots (-3 to -7 %) compared to the P-fertilised plots (-8 to -9 %).

"Soil phosphorus (P) mining in agriculture – Impacts on P availability, crop yields and soil organic carbon stocks", S. Vandermoere et al., Agriculture, Ecosystems and Environment 322 (2021) 107660 https://doi.org/10.1016/j.agee.2021.107660

Legacy P drawdown and maize yield

In two out of three cases, no phosphorus fertiliser application for two years resulted in lower maize yields after one or two years despite estimates suggesting that soil Legacy P was sufficient.

The study is based on the authors' "SPSC" (Soil Phosphorus Storage Capacity) indicator (Nair & Harris 2004). SPSC is based on the difference between 0.1 and "Phosphorus Saturation Ration" (PSR), where PSR is Mehlich-3 P divided by (Mehlich-3 extractable aluminium + iron). A negative is intended to indicate potentially "mineable Legacy P".

Three sites were selected in Florida, USA, where soils showed low negative SPSC, that is potential for P-mining according to the model, but not high soil Legacy P. These sites had Water Soluble Phosphorus (WSP) of 4 -15 and Mehlich-3 P of 69 – 89 mg/kg at the surface (0 – 15 cm).

Rye, silage maize and forage sorghum were grown in rotation for two years, with either 20 kgP/ha per cropping cycling or zero phosphorus (and with agronomic recommended N and K in both cases). Silage maize crop yield was assessed.

At the site with the lowest soil P (WSP and Mehlich-3 P as above) and initial SPSC = -79 mg/kg, crop yield was significantly lower in both the first and second year of no-P fertiliser. At the second site, initial SPSC = -77 mg/kg, yield was lower (but not statistically significantly) in the first year, and significantly lower in the second year. At the third site with the highest initial soil P, initial SPSC = -83 mg/kg, yield was marginally lower in the second year with no-P fertiliser, but not statistically significantly.

The authors note that SPSC calculated after each crop (as a function of soil P level changes) show relation to maize yield.

However, **at the soil P levels tested**, SPSC does not appear as a viable indicator of whether Legacy P is sufficient for crop needs, and that **in most cases crop yield was lower when P fertiliser was not applied**.

"Mining of soil legacy phosphorus without jeopardizing crop yield", V. Nair et al., Agrosyst Geosci Environ. 2020;3:e20056 https://doi.org/10.1002/agg2.20056

Other references:

"Soil Phosphorus Storage Capacity for Environmental Risk Assessment", V. Nair & W. Harris, Advances in Agriculture, vol. 2014, Article ID 723064, 9 pages, 2014, https://doi.org/10.1155/2014/723064

"Soil phosphorus saturation ratio for risk assessment in land use systems", V. Nair, Front. Environ. Sci., 10 April 2014, https://doi.org/10.3389/fenvs.2014.00006

"Consistency of the Threshold Phosphorus Saturation Ratio across a Wide Geographic Range of Acid Soils", B. Dari et al., Agrosyst. Geosci. Environ. 1:180028 (2018) https://doi.org/10.2134/age2018.08.0028

100-year trial shows P movement down in soil

Maize grain yield was several times higher in manure fertilised plots compared to no-fertiliser in a century-long field trial. However, if manure application is targeted to nitrogen needs, this can lead to soil phosphorus accumulation.

Data for maize yields from the Knorr-Holden experimental plot, Scottsbluff, Nebraska, along with soil P accumulation is discussed in this publication. In 1910, the native short-grass prairie soil was broken. From 1942, cattle manure was applied at zero or 27 kg/ha/y. From 1953, the plot area was extended and divided into with/without manure and in each case with different levels of inorganic N fertiliser. Over the century, the maize cultivars and weed and pest control methods evolved with farming methods.

Over the first thirty years, without fertilisation, maize yields fell slowly and significantly, as nutrient stocks in the natural soil were depleted. In the first year of manure application, yields increased seven-fold.

Maize yields were significantly higher in the fertilised plot (e.g. mean 3.1 t/ha 1942-1952) compared to the non-fertilised plot (0.8 – 2.8 t/ha over the same period).

In non-manured plots, yields were correlated to inorganic nitrogen fertiliser application, but not in manured plots, showing that at this level of manure application adding chemical fertiliser was unnecessary.

When yield reliability was assessed, best results were generally achieved in the manured plots, or in plots with high N fertiliser application and which had received manure in the past, suggesting that P and other nutrients availability and associated soil improvement due to manure may contribute to good yield reliability.

Long-term manure application also increased soil organic carbon, by an average 10 mgSOC/kg soil, which may also support yield reliability.

The authors note however that the manured plots showed increased soil P (Olsen-P 20 mgP/kg at 120 – 150 cm depth) indicative of excess P application and risk of P losses.

"Maize yields from manure and mineral fertilizers in the 100-year-old Knorr–Holden Plot", B. Maharjan et al., Agronomy Journal. 2021;113:5383–5397 https://doi.org/10.1002/agj2.20713

119-year trial shows benefits of P fertilisation

Oklahoma winter wheat fertiliser trial running since 1899 (initially with manure, then also with mineral fertilisers since 1930) shows average yields (1967_2018) twice as high with NPK fertiliser or manure, compared to no fertiliser or only P fertiliser.

Cattle manure was applied at c. 10 kgP/ha/y and 34 kgN/ha/y from 1899 to1966, then at c. 20 kgP/ha/y. and 67 kgN/ha/y. From 1967, some plots received instead either NPK or P only fertiliser, at the same N application rate and 25 kgP/ha/y and (for NPK) 28 kgK/ha.

Wheat grain yields were not significantly different (1967-2018) between plots receiving manure and plots receiving NPK fertiliser, but plots receiving only P fertiliser were around half as high, and plots receiving no fertiliser were marginally lower than plots receiving P fertiliser only.

In the fertilised plots (manure or NPK), virtually all of the added phosphorus was accounted for, either identified as still present in soil or taken off in crops. Nearly all of the remaining P from the NPK fertiliser was present in the top 15 cm of soil, whereas around 40% of the P from manure had moved down to 30 – 90 cm soil depth. Manure P had not however reached deeper than 90 cm.

The authors conclude that even after over a century of manure application, leaching to groundwater is not a concern at this site.

"Recovery of Phosphorus in Soils Amended with Manure for 119 Years", A. Pasket et al., Agronomy 2020, 10, 1947; https://doi.org/10.3390/agronomy10121947

70 years data from pasture field trial

Data adapted from the Winchmore trials of fertilised, grazed pastures, established 1948-1949, Canterbury, New Zealand, show that stopping P fertiliser application results in a drop in grass yield, from more or less the first year and continuing to fall over 10 – 20 years.

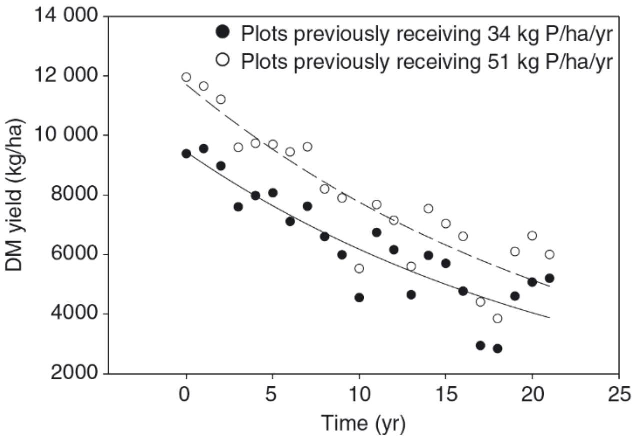
These data are compared to data from three other pasture trial sites where P fertiliser application has been stopped, since 7, 16 or 26 years, following previous fertiliser application (at 10 – 100 kgP/ha,at Whatawhata and Ballantrae, and following previous zero fertilisation (Lincoln).

The Winchmore site shows that after around twenty years of P fertiliser application at 34 or 51 kgP/ha, **stopping P application led to a small loss in grass crop yield already in the first years. Yield then fell progressively to below half of levels achieved after the years of fertilisation within 10 – 15 years**.

Soil phosphorus (Olsen-P, WEP and at one site also calcium chloride extractable P) also decreased following stopping P fertilisation.

At Winchmore, the decline in yield was comparable to the decrease in soil WEP (water extractable phosphorus).

The authors conclude that **halting P fertilisation in grazed pasture may result in unacceptable losses to farm productivity**.



Graph above: Yield decrease following stopping P fertilisation at Winchmore, adapted from fig. 9 (dry matter production residual treatments 1958/9 to 1979/80) in Rickard & McBride 1987 "Long term application and residual effects of superphosphate and effects of reactive phosphate rock on irrigated pasture". Winchmore Irrigation Research Station Technical Report 22.), in Dodd et al. 2012.

"Predicting the changes in environmentally and agronomically significant phosphorus forms following the cessation of phosphorus fertilizer applications to grassland", R. Dodd, R. McDowell, L. Condron, Soil Use and Management, June 2012, 28, 135–147 *https://doi.org/10.1111/j.1475-2743.2012.00390.x*

"Seventy years of data from the world's longest grazed and irrigated pasture trials", R. McDowell, R. Moss, C. Gray, L. Smith, G. Sneath, Scientific Data, (2021) 8:53 | *https://doi.org/10.1038/s41597-021-00841-x*

High soil P depends on fertiliser inputs

Ten-year trial in Ireland shows, on grazed permanent pasture, that P fertiliser inputs over 5 years increase the soil P pool, but that this falls back to initial levels after 5 years without fertiliser application.

Previous tests on the plots at Hillsborough, County Down, Northern Ireland, are reported in Watson et al., below. From 1994 to 1999, all plots concerned by this study received 8.3 kgP/ha/y, that is recommended levels for grazed grassland, with variable levels of nitrogen (100 – 500 kgN/ha/y). Offtake of phosphorus in animals (beef livestock) is estimated at c. 8 kgP/ha/y.

From 2000 to 2005 plats received 0, 20, 40 or 80 kgP/ha/y, that is up to ten times agronomic recommended application. From 2005 to 2010, all plots received zero phosphorus input. Grazing continued throughout.

Soil phosphorus increased significantly in the fertilised plots by 2005, with similar increases for Mehlich P, Olsen-P and WEP. Mehlich P, for example, increased from 60 - 80 over 1994 – 2000 to nearly 200 in 2005 (@ 80 kgP/ha/y). **But in all cases, soil P returned to close to initial levels after five years of grazing without P-fertiliser input**.

In the plots **with no P fertiliser input from 2000 to 2010, final soil P levels were significantly lower after ten years** compared to initial levels.

Few significant modifications in forms of phosphorus in soil were detected by P-NMR in 2010. However, soils having received mineral fertiliser then no-fertiliser showed higher inorganic P and soils which had received no-fertiliser for ten years showed higher inositol, monoester and diester (organic) phosphorus forms.

In a previous study, Watson et al. 2008 showed that on these plots, after initial reseeding of grass in 1987 then grazing as permanent pasture, **phosphorus losses in drainage water were "well above" concentrations sufficient to trigger eutrophication, when P was applied at agronomic recommended levels** (8.5 kgP/ha/y). P losses were not modified by level of N fertiliser application.

Net P input was estimated to be zero (offtake in livestock produced, based on livestock numbers and animal weight, equivalent to fertiliser P input), but nonetheless total P in surface soil (0 – 5 cm) increased significantly (nearly 25% increase over ten years), possibly by root and earthworm activities. The authors note that this surface accumulation is likely to exacerbate losses by runoff.

"Long-term Changes in Grassland Soil Phosphorus with Fertilizer Application and Withdrawal", B. Cade-Menun, D. Doody, C. Liu, C. Watson, J. Environ. Qual. 46:537–545 (2017) *http://dx.doi.org/10.2134/jeq2016.09.0373*

"A 10-year study of phosphorus balances and the impact of grazed grassland on total P redistribution within the soil profile", C. Watson, D. Mathews, European Journal of Soil Science, December 2008, 59, 1171–1176 *http://dx.doi.org/10.1111/j.1365-2389.2008.01083.x*

'Impact of grazed grassland management on total N accumulation in soil receiving different levels of N inputs", C. Watson, C. Jordan, D. Kilpatrick, B. McCarney, R. Stewart, Soil Use and Management, June 2007, 23, 121–128 http://dx.doi.org/10.2134/jeq2006.0207

Modelling Legacy P watershed impacts

Modelling of P-losses in Lake Okeechobee watershed, Florida, suggest that "Legacy P" from improved dairy pastures contribute 2/3 of total phosphorus inputs and inorganic fertilisers only 10%.

The study is based on detailed modelling using WAM (Water Assessment Model), combined with various sub-modules (LOW, TCNS, BUCSHELL, EAAMOD, GLEAMS, BLASROUTE). Legacy P losses are estimated from literature (SWET South Florida Water District 2007, HDR University of Florida 2010) which compiled data on soil chemistry in the Lake's watershed according to land use. These studies indicate high variability in legacy P, e.g. 180 – 750 kgP/ha accumulated phosphorus for improved pasture, or 300 – 9750 kgP/ha for active dairy farms.

Modelling suggests that around 2/3 of total load of phosphorus to Lake Okeechobee is from legacy P, mainly in improved dairy pastures, but also in abandoned dairy farms and citrus plantations, and only around 10% from mineral fertiliser application.

The authors conclude that BAMP (Best Agricultural Management Plan) actions are essential to mitigate losses of legacy P, such as the Florida Targeted Restoration Area actions, and that evaluations of possible impacts of climate change on legacy P losses to the lake should be assessed.

"Watershed Response to Legacy Phosphorus and Best Management Practices in an Impacted Agricultural Watershed in Florida, U.S.A.", Y. Khare et al. Land 2021, 10, 977, https://doi.org/10.3390/land10090977

Manure and phosphorus losses

Soil lysimeter tests suggest P leaching is influenced by manure organic matter, soil structure and form of phosphorus.

54 undisturbed soil columns 30 cm diameter x 50 cm depth were collected from three sites in Delaware, with soil P in the environmental to optimum range, then used as lysimeters. These were irrigated with 50 mm water per week for 8 weeks, then fertiliser or manure was applied. Total and dissolved phosphorus (DRP) were measured through to 16 weeks.

Before fertiliser application, total and dissolved P losses were not significantly different between environmental and optimum P level soils (Mehlich-P saturation ratio < 0.1 and >0.15).

Six different fertiliser treatments at 8 weeks were: no P (control) or fertilisation at 86 kgP/ha as triple super phosphate mineral fertiliser, high or low P dairy manure and high or low P poultry manure. The P content of the dairy manure depended on P content of diet, and was 0.84% or 0.57% total P. The P content of the poultry manure depended on whether phytate was used (to reduce diet P requirement) and was 1.36% or 0.97%.

Higher P leaching showed in soils which allowed rapid preferential P transport through macropores, with short-term peaks following fertilisation. Soil with significant iron and aluminium levels showed lower DRP leaching, as phosphorus was retained by these minerals in soil. Nonetheless, phosphorus was found in both DRP and non-dissolved form in leachate from all soils.

Mineral fertiliser tended to result in higher leaching of DRP than manure.

Counter-intuitively, the **low P manures resulted in higher P losses than the high P manure**. This is surmised to be because higher loadings of the low P manure were applied (to achieve the same P application rate) resulted in higher levels of organic matter, which may have impacted P adsorption to the soil or caused P transport with transport of organic carbon.

"Managing Phosphorus Leaching in Mid-Atlantic Soils: Importance of Legacy Sources", G. Toor & J. Sims, Vadose Zone J., 2015 https://doi.org/10.2136/vzj2015.08.0108

"Managing legacy and new sources of phosphorus to reduce leaching in Mid-Atlantic soils", G. Toor & J. Sims, Crops & Soils magazine, September–October 2016 https://doi.org/10.2134/cs2016.49.0512

"Phosphorus Leaching in Soils Amended with Animal Manures Generated from Modified Diets", G. Toor & J. Sims, J. Environ. Qual. 45:1–7 (2016) https://doi.org/10.2134/jeq2015.10.0542

Buffer strip remains effective after 50 years

The vegetated buffer strip (VBS) studied was 5 – 35 m wide, with permanent grass and sedge vegetation, and had been in place for nearly 60 years (1954 – 2011) along the bank of a stream near Elma, Whitemouth River catchment, Manitoba, Canada.

The upstream field was recently planted with wheat and soy under conventional tillage, and had a previous history of pig manure injection. Field surface runoff from the field descends to the buffer strip.

Soil samples from the buffer strip and the cultivated field were compared to those from a nearby reference site under permanent pasture with no cultivation for at least 50 years.

Soil carbon dating shows significant soil erosion in the field, despite relief of < 1m and < 2% slope, and sediment accumulation in the buffer and in 'ponding' in the field at edge of the buffer strip.

Soils at the buffer strip – field limit showed significantly increased P content, compared to sites in the cultivated field, indicating phosphorus storage in this ponding area. Soils 5m into the buffer strip showed significantly lower soil-P, indicative of low potential P-release to surface waters and a continuing capacity to trap phosphorus.

The study shows that in this case, where most P-losses from the cultivated field are particulate, and with 'ponding' between the field and the vegetated buffer strip, **the buffer strip continues to be effective after nearly six decades as a P-trap, reducing loss of Legacy Phosphorus to surface waters.**

"Effectiveness of Vegetated Buffer Strips in Controlling Legacy Phosphorus Exports from Agricultural Land", R. Habibiandehkordi et al., J. Environ. Qual. 48:314–321 (2019) https://doi.org/10.2134/jeq2018.04.0129

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