Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-176
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 10 April 2018

Hydrology and Earth System Sciences
Open Access
Discussions

Global Phosphorus Recovery for Agricultural Reuse

Dirk-Jan D. Kok[1*], Saket Pande[1], Jules B. van Lier[1], Angela R.C. Ortigara[2], Hubert Savenije[1], Stefan Uhlenbrook[1,2]

[1] Department of Water Management, Delft University of Technology. Delft, Netherlands.
[2] World Water Assessment Programme, UNESCO. Perugia, Italy.

Correspondence to: Dirk-Jan Kok (D.D.Kok@cml.leidenuniv.nl)

Abstract. Phosphorus is is an element necessary for the development of crops and is thus commonly applied as fertilizer to sustain agricultural production. It occurs naturally at indefinite quantities, of uncertain quality, in phosphate rock formations, but also concentrates itself in urban and livestock wastewater wherefrom it is often lost as a pollutant. Recovering phosphorus from wastewater to partially meet agricultural demand can contribute to tackling both phosphorus pollution as well natural resource depletion. Here we show that humans discharge a maximum of 3.7 Mt P into wastewater thereby potentially satisfying 22% of the global fertilizer demand. Provided 2015 market dynamics, however, we conclude that only 4% of this throughput is technologically and economically recoverable while rock phosphate products exist. Nonetheless, through this recovery, many wastewater treatment facilities can contribute to creating sustainable communities as well as protecting the environment while reducing their own operational cost.

Key words: *Phosphorus, circular economy, wastewater, struvite, fertiliser*

1 Importance of Phosphorus

Phosphorus (P) is an element necessary for the development of all living beings as it forms an unsubstitutable, key structural component of DNA and RNA. It is applied to crop lands in the form of organic fertilizers or synthetically as single or triple superphosphate, or mono-Ammonium or di-Ammonium Phosphate (DAP), which are easy to transport, to distribute over fields, and are readily absorbed by plants. The most essential resource for the production of synthetic phosphorus fertilizers is phosphate rock.

The rates at which we exploit phosphate rock formations is out of proportion to the rates at which they form - essentially classifying phosphate rock as a non-renewable resource. Peak production of phosphate ore could occur as early as 2030 (Cordell et al., 2009) with economically extractable (high quality and low heavy metal content) P resources becoming scarce or exhausted within the next 50 to 100 years (Smil, 2000; Steen, 1998; Van Vuuren et al., 2010)[1,2]. The prospect of phosphorus depletion threatens global food security, where especially regions of poor soil nutrition levels are vulnerable to its effects. The gradual depletion process will result in further reduction of fertilizer accissbility by small-holder and subsistence farmers that comprise areas already struggling to cope with food shortages (Pande and Savenije, 2016).[3]

[1] With the remaining, non-economically explotiable ore being too costly to process due to its poor quality – i.e. low phosphorus and high heavy metal content.
[2] Others authors predict that reserves will last another 300-400 years (van Kauwenbergh, 2010)
[3] Sub-Saharan Africa (SSA) is one such region, as nearly 75% of SSA's agricultural soils are nutrient deficient already contributing significantly to the crop yield gaps (Sanchez et al., 1997).

1.1 Turning brown waste to green gold

The introduction of intensified (P) fertilization during the Green Revolution of the 1960's demonstrated P's significant potential to improve crop yields, but also the dangers it poses to the environment. Through seepage and runoff processes, as well as the discharge of improperly treated wastewater, phosphorus and other nutrient excesses come into contact with open surface waters, cause pollution, and lead to a loss in aquatic biodiversity (Sims et al., 2000).[4] As a limiting nutrient, the smallest quantity of phosphorus in water can spark the growth of disproportionately large algal blooms. These have a detrimental effect on water based ecosystems in suffocating aquatic life through eutrophication (EPA, 2010).[5] If excess fertilization is a major threat to water quality around the world, then why not extract this excess from the water system and put it back in the food chain? Proper nutrient management practice in tandem with nutrient recovery from rural and urban water systems may potentially be an important strategy to reduce phosphorus pollution by reducing phosphorus discharge to the environment while simultaneously increasing phosphorus supply for food production.

Numerous phosphorus recovery technologies are available; their effectiveness varying, among others, with local wastewater composition and existing wastewater treatment infrastructure. While there exist numerous studies on the efficiency of specific recovery technologies, on the potential recovery from wastewater, and on the duration of the rock phosphate reserves, there are few studies that evaluate recovery in a global and economic context. As such, the adoption of phosphorus recovery technologies is often challenged by (perceived) economic infeasibility or lack of economic incentives and social stigma. Hypothetically, however, the economic feasibility of recovery is not globally homogeneous but varies in space and time. Spatially, the global accretion of phosphorus in wastewater provides recovered products with a (diffused) location-defined competitive advantage over the geographically concentrated rock phosphate mines (fig. 1). Temporally, the gradual depletion of rock phosphate reserves, and the unstable but increasing price trends for non-sustainable phosphatic fertilizers (IndexMundi, 2017), will improve the economic appeal for recovery over time (fig. 2).[6]

1.2 Motivation

Though various factors such as the political will, technology and knowledge are already there to facilitate the transitioning of the phosphorus market, the economic appeal for recovery still lags behind. Favourable economic prospectives, however, are spatially diverse and will strengthen over time. Global studies that identify locations and conditions for competitive phosphorus recovery at subnational scale could accelerate this transition but are currently inexistent. This study aims to fill that gap by identifying and connecting those areas where there exist high potentials for phosphorus production, to those areas of high agricultural demand. Revealing where recovery may be economically feasible may then stimulate the implementation of recovery technologies, or at least promote further investigation in those areas that show a high potential for recovery.

The phosphorus cycle is delineated by combination of both social and physical attributes and as such demands a coupled

[4] In 1990 about 43% of the grassland and 82% of the maize land in the Netherlands was approximated to be saturated in nutrients due to over fertilisation (Breeuwsma and Silva, 1992). As a result, the nutrient concentrations in surface waters in The Netherlands still consistently exceed water quality standards (Oenema et al., 2007; Oenema and Roest, 1998).

[5] These deoxygenated "dead zones" can be found in both lakes and seas, and affect an estimated 245,000 km2 of marine ecosystems (Corcoran et al., 2010).

[6] Over the past 15 years the phosphorus price of DAP has increased from 665 [$ t^{-1}] to 1,552 [$ t^{-1}]. In that same period, the price has been as high as 5,217 [$ t^{-1}] (2008) and as low as 656 [$ t^{-1}] (2002) (IndexMundi, 2017).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-176
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 10 April 2018

human water systems perspective. A socio-hydrological approach is endeavored as here both these attributes are expressively and emphatically accounted for (Sivapalan et al., 2012). The social component, however, of this coupled human-phosphorus system is confined to the characteristics of a distinct economic nature. The materials and methods employed in assessing the recovery potential of P from waste water at global scale is therefore interdisciplinary and extensive, and covers largely economics within a sciences context.

2 Materials and Methods

An integrated approach is required to identify locations and conditions for competitive phosphorus recovery at global scale. This comprises of:

1. **Identification of sites and quantities:** Identifying where in the world phosphorus-laden wastewaters and agricultural areas concentrate themselves, and assessing the associated, approximate phosphorus production and demand quantities.
2. **Determination of node prices:** Approximating the minimum production costs of different production sites, and maximum paying prices of varying crop sites respectively.
3. **Modelling international trade** in phosphorus, which involves:
    a. *Determination of global market price:* Determining an international, free-market price for phosphorus as a function of P-quantities, prices, and distances between the different sites.
    b. *Trade flows corresponding to the market price:* Visualizing a realistic network of phosphorus trade fluxes for different market prices.

Geographic Information System (GIS) tools (Q-GIS 2.14) (Quantum GIS Development Team, 2017) are used to pre-process spatial data for utilization by the trade network model built in Python 3.6.

2.1 Identification of Sites and Quantities

Using population density maps (Robinson et al., 2014), globally generalized phosphorus excretion rates (Barker, Hodges, & Walls, 2001; CBS, 2014; Gilmour, Blackwood, Comber, & Thornell, 2008), and phosphate mine production rates (USGS, 2002, 2007), a crude, global mapping of phosphorus production sites is achieved. The *sustainable* phosphorus production potential is roughly approximated through globally generalized, maximum phosphorus throughput figures and population density maps for humans, cows, pigs and chicken (see Table S1 in supplementary materials), which are related through the following formulation:

$$S_{PO} = (P_{DO} * O_{PP}) * E_{rO} \quad (1)$$

where S_{PO} is the maximum organic phosphorus production density [kg km^{-2} a^{-1}]; P_{DO} is the population density [h km^{-2}]; O_{PP} is the phosphorus throughput rate [kg h^{-1}a^{-1}]; and E_{rO} is the estimated recovery efficiency [-] for the group O, of humans, pigs, livestock, or poultry (see section 2.2).

The phosphorus demand density is assessed through crop harvested area maps for six major crops. The P demands for maize, wheat, rice, sorghum, soy bean, and potato are approximated as the minimum amount of phopshorus needed to realize water-constrained yield. These yields are determined through the evaporation-transpiration deficit approach (Steduto et al., 2012). The adapted equation is described as followed (eq. 2):

$$1 - \frac{Y_a}{Y_m} = K_y\left(1 - \frac{E_a * \frac{T_g}{365} * A_H * C}{E_m}\right) \quad (2)$$

where Y_a is the actual yield [kg km-2 a1]; Y_m is the optimal yield [kg km^{-2} a^{-1}]; K_y is the crop coefficient [-]; E_a is the actual evaporation-transpiration [mm a^{-1} Area^{-1}]; T_g is the crop growing period [d]; A_H is the fractional area harvested [-]; and C [-] is a correction factor that accounts for the induced error by the 'annual approach' to the evapotranspiration-deficit equation – scaling the maximum yield ratio globally to be no greater than 1. E_m is the evaporation-transpiration for optimal yield [mm a^{-1} km^2], which is assumed equal to the crop water requirement for optimal yield. The associated phosphorus requirement for this yield is determined through a linear regression between yield and P-fertilizer application as described in eq. 3.

$$\mathrm{D_{PT}} = \frac{\mathrm{Y_a}}{\mathrm{Y_m}} * P_{opt}^{n} * \mathrm{A_H} \quad (3)$$

where $\mathrm{D_{PT}}$ is the total P-demand [t ha^{-1}a^{-1}]; P_{opt}^{n} is the crop specific P-demand for optimal yield [t ha^{-1}]; and $\mathrm{A_H}$ is the crop harvested area [ha^{-1}]. The parameters per crop are summarized in Table S2 of the Supplementary Materials. These six crops make up roughly 56% of the global demand (Heffer, 2009). Although spatially unrepresentative of the actual global phosphorus demand distribution, the total demand can be approached by dividing the pixel values for the six major crops by 0.56 (56%).

The areas of major production and consumption densities are aggregated into nodes that are described by a coordinate position, a class (group: urban or livestock, or crop type), and a quantity of yearly phosphorus supply or demand. Nodes with a production of less than one kilo tonne per year for livestock, and less than 400 tonnes demand per year for urban/rural sites, are considered insignificant in the global context and are therefore excluded from further consideration. This constrains the total number of actors, reduces the complexity of the network, reduces the processing time required, and improves visualization of the results. In the visualizations, the remaining nodes will be stylized to vary in size according to their annual P production and demand potentials [kt a^{-1}] to make the significant actors more easily identifiable.

2.2 Determination of Node Prices

Whether trade is possible between a demand and a production node depends on the transportation and production costs of the production node and the maximum bid price of the demand node. The production cost varies depending on the recovery technology, whose feasibility for implementation depends on wastewater composition and existing infrastructure. In this study, municipal wastewater composition is assumed roughly, globally homogenous, while the Sustainable Development Goals dataset on *percent of urban population with access to sanitation* is used to derive an approximation on the development status of existing sanitary infrastructure (WHO/UNICEF JMP, 2015). A high (>90%) national percentage of urban population with access to saniation is likely to be indicative of highly developed countries that observe stricter effluent standards and that therefore have, or are working towards upgrading, conventional wastewater treatment plants (WWTP) for biological nutrient recovery (BNR) or chemical phosphorus removal. The phosphorus recovery costs for the BNR-WWTP group of nodes are those associated with the investment in a large Ostara® Pearl Reactor for struvite precipitation, recovering 20% of the influent wastewater's phosphorus loading (Schoumans et al., 2015). Although other struvite recovery technologies are available, this one was chosen given its commercially effective implementation in various different countries. The production cost for the highly developed group is reduced due to savings in uncontrolled struvite scaling maintenance and sludge handling. Areas with intermediate urban access (40-90%) are assumed to be serviced by a simple, centralised wastewater treatment facility. The technology investment cost for these nodes are the same as for the the highly developed infrastructure group but excluding this time the sludge handling cost savings. Lastly, low urban access (<40%) is assumed to be indicative of low sanitary development and thus offers the flexibility to adopt more novel, less water dependant forms of sanitation. The technology applied for these areas are source separating-, dry composting toilets, where urine and fecal compost are collected separately. The urine is collected by 40,000 litre tank trucks and processed at a centralized struvite precipitation facility. Fecal compost is collected, dried and processed into compost pellets at a central facility. For livestock farms this compost pelleting technology is also applied, but occurs on-site.

The recovery efficiency factors (E_{rO}) in eq. 1 depend on the recovery technology applied for each organism group O (humans, pigs, poultry, cows). A phosphorus recovery efficiency of 20% of the influent is taken for struvite crystallization in wastewater (Schoumans et al., 2015); while a 90% efficiency can easily be achieved when struvite precipitation is applied on source-separated urine (Wilsenach et al., 2007). An efficiency of 85% and 75% for cattle and swine, and poultry respectively is assumed for pelletization of composted livestock waste.

For production nodes, a generalized struvite precipitation cost is determined by the following (eq. 4):

$$f_{min}^{i} = \frac{R^{S} * S_{PT} + B^{S}}{S_{PT}} - S + \frac{T^{i}}{\rho} \qquad (4)$$

where f_{min}^{i} is the minimum price for phosphorus produced at node i [\$ t^{-1}]; R^{s} is the resource cost [\$ t^{-1}] P; B^{S} fixed operational cost [\$]; S_{PT} is the total phosphorus production potential [t]. Where relevant, S is the struvite scaling and sludge handling cost savings [\$ t^{-1}] P (i.e. for for BNR plants); T^{i} is the intracity transport cost of collection [\$ t^{-1}] (i.e for source-separating toilets); and ρ is the proportion of phosphorus by weight of the transported material [kg kg^{-1}], which are 0.066% and 0.46% for urine and dried, faecal, toilet compost respectively (Bjorn Vinnerås, 2001). The annual fixed operational costs are taken as the annual costs minus the resource costs as reported by Egle (n.d.). The resource costs (i.e. $MgCl_2$) are calculated separately. Mostly, these are a function of the magnesium chloride price (P_m) and the ratio of magnesium required per ton of phosphorus (R_{mp}). For BNR plants, a struvite and sludge handling cost savings is included of 0.89 [\$ kg^{-1}] struvite removed (Shu et al., 2006) This essentially allows BNR plants to supply struvite for free (excl. transportation costs). The additional resource cost for the dry-toilet solution is attributed to the collection of waste and a pelletization cost of \$30 [\$ t^{-1}] compost (Masayuki Hara, 2001). T^{i} is described as followed (eq. 5):

$$T^{i} = D_{ta} \frac{P_d * E_{Lt} + \frac{L_{ct}}{V_{Lt}}}{W_{Lt}} \qquad (5)$$

Where D_{ta} is the average distance of a return journey for a tanker truck in servicing the city, approximated at 20 [km]; P_d is the price of diesel [\$ L^{-1}]; E_{Lt} is the fuel efficiency of the tanker truck, 0.016 [L km^{-1}]; L_{ct} is the labour wage, 10 [\$ h^{-1}]; $\bar{V}_{Lt}$ is the average velocity of the truck in the city, 50 [km h^{-1}]; W_{Lt} is the truck load weight, 40 [t].

The maximum price that demand nodes are willing to pay depends on the marginal value of phosphorus. This varies per crop type and can be described as followed (eq. 6):

$$f_{max}^{n} = \frac{Y_{opt}^{n} * C_{a}^{n}}{P_{opt}^{n}} * \ R^{n} \tag{6}$$

where f_{max}^{n} is the maximum price for phosphorus [\$ t^{-1}]; Y_{opt}^{n} is the optimal yield [t ha^{-1}]; C_a^n is the crop price in year *a* [\$ t^{-1}]; P_{opt}^{n} is the optimum fertilizer dosage rate (equal to total P-requirement for optimal, water constrained yield) [t ha^{-1}]; and R^n is the ratio of fertilizer cost to total production costs [-], for crop *n*.

Lastly, the transportation costs are determined with *as-the-crow-flies* distances with the parameters given in Table S3 (see Supplementary Materials) substituted into the following transport cost equation (eq. 7):

$$T_c^{i,n} = D^{i,n}\left[F_W * \frac{P_b * E_W + \frac{C_F}{\bar{V}_W}}{W_W} + F_L * \frac{P_d * E_L + \frac{L_C}{\bar{V}_L}}{W_L}\right] \tag{7}$$

where $T_c^{i,n}$ is the transportation cost from node i to node n [\$ t^{-1}]; $D^{i,n}$ is the distance between node *i* and node *n* [km]; P_b is a bunker fuel price [\$ t^{-1}]; P_d is the price of diesel [\$ L^{-1}]; E_W is the fuel efficiency of a full handy size bulk carrier [t d^{-1}]; E_L is the fuel efficiency of a 2x30 tonne truck combination [L km^{-1}]; C_F is the fixed costs per ship [\$ d^{-1}]; L_c is the labour wage [\$ h^{-1}]; $\bar{V}_W$ is the average velocity of the carrier over water [km d^{-1}]; $\bar{V}_L$ is the average velocity of the truck over land [km h^{-1}]; W_W is the carrier load weight [t]; W_L is the truck load weight [t]. F_W and F_L are the fractions of the total distance that is travelled over land and over sea. The model at present does not distinguish between the transportation over land and over sea based on observed geography. Instead the model employs a cumulative probability curve that approximates the proportion of the total distance likely to have been traversed over water, F_W (eq. 8); and over land, F_L (eq. 9), where it is assumed that at least 15% of the total distance is always transversed over land.

$$F_w = \frac{85}{1+e^{-\frac{D-\mu}{S}}} \tag{8}$$

$$F_L = \frac{85}{1+e^{\frac{D-\mu}{S}}} + 15 \tag{9}$$

where μ and S are function shape constants of 500 and 100 [-], respectively.

Hydrology and Earth System Sciences Discussions
Open Access

2.3 Trade model

First, the model determines the optimal price for international phosphorus trade. Then, a trade network is created that identifies the nodes involved in trade and quantifies the amounts they exchange at the determined price. These two steps are taken for three different market scenarios:

1) **Current market - mine supplied products only:** The current phosphorus market is strongly rock-phosphate oriented. When the model runs the data for a 'current market' scenario, only rock phosphate products are available on the market.
2) **Future market - both mine and recovered products:** Recovered phosphorus is likely to become a more important product in the future market. When the model runs the data for a 'future market' scenario, it is assumed that both rock phosphate as well as recovered phosphorus products partake.
3) **Far-Future market - only recovered products:** In the far future market, most rock phosphate reserves will have been depleted. When the model runs the data for a 'far-future' scenario, it is assumed that rock phosphates no longer take part in the market which is then solely dominated by sustainable, recovered products.

2.3.1. Determination of global market price

The global market price is determined as the price at which total quantity of phosphorus demanded is equal to the quantity supplied (i.e. the market for P is cleared; (Arrow and Debreu, 1954)). This is approximated as the point where global demand function for phosphorus intersects the global supply function. The demand function is the locus of the maximum prices at which demand nodes are willing and able to purchase phosphorus, and the supply function is the locus of minimum prices at which supply nodes can sell certain amounts of phosphorus without going out of business (i.e. without making a loss). The Supplementary Text provides an illustration of how market prices for the three scenarios are determined and how transportation costs complicate the determination of supply function and hence the determination of global market price for phosphorus.

2.3.2. Quantification of Trade Flows

The following steps are taken in order to identify trade flows. Firstly, a list of all possible combinations of supply and demand nodes is created, which is passed through two 'filters' for a given 'hypothetical market' price. The first filter removes the pairs that can never trade with each other based on their combination of the minimum production costs, the maximum price boundary and transportation costs (which happens when productions costs are higher than the revenues that a supply node can generate by selling to a demand node). The second filter removes node pairs which cannot trade with each other at a given 'hypothetical market' price imposed on the network. This occurs when the production cost is above the imposed market price.

In the model, phosphorus consumers will look for the cheapest suppliers. The matter becomes obscure here as, in reality, there are no cheaper or more expensive suppliers when there is a single, set market price (note that single set market price is different from the 'hypothetical market' price mentioned above). However, supply nodes that could supply at prices far lower than the set market price (due to lower production costs) have a competitive advantage over those that cannot. The difference between these 'hypothetical market'- and actual market price shows how competitive a node is. If a node pair is *able* to trade at a much lower price than market price, then the model assumes that this trade occurs first. These nodes have the power to undercut their (more expensive) competitors and safeguard their own favourable trading position. This concept (i.e. the notion of hypothetical markets) is essentially used to identify most likely trade partners so that in the end a global trade network can be created that trades at one global price of recycled P.

For different 'hypothetical market' prices, a list of trade partners is obtained by executing the trade at each price, and updating the list in terms of total phosphorus quantity (*Q)* demanded by demand node (*D*) number *n,* or supplied by supply node (*S*) number *i* (D_Q^n, and S_Q^i, for demand and supply respectively). The amount traded ($Q_{(i,n)}$) between each node pair is taken to be equal to the minimum of supply or demand as formulated below (eq. 10):

$$Q_{(i,n)} = \begin{cases} S_Q^i & if\ D_Q^n > S_Q^i; \\ D_Q^n & if\ S_Q^i > D_Q^n; \end{cases} \tag{10}$$

The supply available and quantity demanded at each supply demand nodes are updated as follows (eq. 11),

$$\begin{matrix} S_Q^i = 0, & D_Q^n = D_Q^n - Q_{(i,n)} & if\ D_Q^n > S_Q^i; \\ D_Q^n = 0, & S_Q^i = S_Q^i - Q_{(i,n)} & if\ S_Q^i > D_Q^n; \end{matrix} \tag{11}$$

By eq. 11, one of the nodes will have 0 production capacity or demand after each trade, and so all possible trade combinations with that node are removed from the list of possible trade partners for that price. This process is continued until the list is empty and thus all feasible trade has been conducted for that price. The traded pairs are then connected through a series of colored vertices on maps to visualize what the trade network looks like.

2.4. Simulation years

Since most of the data is only available for 2005, the model is designed around the balances of that year. Variable data and parameters such as human and livestock population count, fuel prices, crop value, etc., are adjusted to match the statistical figures for other years when simulating for these other years. For example, the human population density raster used to determine phosphorus production potential was made for 2005 (CIESIN, 2016). In determining the population density and therefore phosphorus production potential of another year, the model adjusts the 2005 population figure through eq. 12 to approach a new population estimate.

$$P_y = P_{2005}(1 + 0.0122)^{y-2005} \tag{12}$$

Where P_y is the population density raster for year *y;* P_{2005} is the population density raster for 2005; and 0.0122 represents the 2005 to 2015 averaged, global human population growth rate of 1.22% per year (World Bank, n.d.). The social phernomena of migration and urbanization are not considered in the process. The model is run for 2005, 2006, 2011, and 2015 through such manner. The adjusted parameters and how their adjusted values compare to the original 2005 data, is shown in Table S4 of the Supplementary Materials. Running the model for several years will not only reveal changes in market dynamics, but also suits a validation purpose. When the model run for a mines-only (current market) scenario, it produces prices for mined P that may be validated against the currently recorded prices for mined P.

3. Results

3.1. Identification of Sites and Quantities

The spatial distribution of phosphorus recovery potential [t km^{-2} a^{-1}] from livestock and humans, as well the global agricultural phosphorus demand, are presented in the Supplementary Figures (S1) at a resolution of 0.08 decimal degree in WGS84 projection. The associated data is summarized per continent in Table 1.

Some continents (i.e. South and North America) show significant disproportionalities in recoverable P from waste vs. phosphorus demand for crop production (Table 1). (Virtual) phosphorus trade (e.g. soy bean products) can play an important role in determining these continental budget surpluses and deficits. In the end, however, the global recovered phosphorus budget is only slightly off balance at 109% total production potential to demand. This global (9%) surplus suggests that there is an inherent overestimation of the phosphorus excretion rates or underestimation of the agricultural phosphorus demand, or that some degree of soil nutrient mining by the crops is considered in the phosphorus requirement values presented in 'Fertilizers and Their Use' (FAO & IFA, 2000). Another explanation for the this disproportion is that non-agricultural consumers of phosphorus (e.g. medicine and detergents industries) are not considered as actors even though their consumed products are included in the wastewater discharge figures.

Unfortunately, however, it is not feasible to recover every ounce of phosphorus excreted, or to fertilize every crop patch everywhere. More realistically, recovery will be economically efficient in areas of high population or livestock density while fertilisation will benefit mainly areas of intensive agriculture. A more realistic assessment of the contribution of recovered products to the global P demand can be made by disregarding production and demand areas of low P density, and selecting only for major production and demand nodes. The results below are discussed following this second more refined and conservative definition of production potential.

3.2. Determination of node prices

The minimum production costs for the production nodes has been determined (fig. 3). The low density of phosphorus (1% phosphorus by weight) results in relatively high production and transportation costs of compost pellets per tonne of phosphorus content. The added value that is not considered in the model is that compost pellets also upgrade the soil in providing substantial amounts of nitrogen and organic matter as well. The significant, general difference in the production cost of P from recycled sources with that of mines means that transportation costs, i.e. distance between trading nodes and fuel costs, will have to play a critical role if sustainable trade in recycled P is to be feasible.

3.3. Trade model results

Based on the methodology presented in section 2, phosphorus quantities, costs, and the distances between the nodes are used to determine market prices at which trade may occur globally to evaluate the economically constrained recovery potential.

3.3.1. Model Validation

Before evaluating the model results, it was necessary to determinehow well or poorly the model approximates the market prices for different years. The model is therefore run for a mines only scenario for 2005, 2006, 2011 and 2015. The produced price ranges for unsustainably sourced phosphorus can then be compared to the observed price ranges for phosphorus in conventional DAP fertiliser for a quick performance assessment (fig. 4). In addition to this, the model results for the other two (more hypothetical) modelling scenarios are included as well.

The boxplots of calculated prices in fig. 4 show plausible ranges for P prices at which trade can occur at global scale. The whiskers on the grey boxes for the observed prices (grey) represent the range within which the price fluctuated during that year, the box itself shows the upper and lower quartiles for that data and the orange line indicates the median. Note that the price range estimated by the model closely follows the range of observed prices within that year for all the simulation years (i.e. 2005, 2006, 2011 and 2015). The price ranges for simulation year 2015 specifically are presented in Table 2, where the minimum price represents the model determined lower boundary of the range, the maximum its upper boundary, and the optimum represents the most realistic price approximation as determined by the model.

3.3.2. Trade flows of conventional and recycled P

The network maps for the 'optimum' market prices from Table 2 are presented for scenario two and three in figures 5 and 6, respectively. Optimal trade in a market of recovered and mined phosphorus products (scenario 2) occurs at a market price of 1,950 [$ t^{-1}] with 16.81 [Mt] being traded in total, of which 0.13 [Mt] is traded sustainably (0.8% of total demand). For a market of only recovered products (scenario 3) optimal trade occurs at a price of 5,700 [$ t^{-1}] with 6.42 [Mt] being traded – all of which sustainable but only satisfying 38% of the total demand. The high recovery potential and close proximity of recovery nodes to agricultural demand nodes makes phosphorus recovery in Asia particularly competitive in both scenarios. The struvite scaling maintenance and sludge handling cost savings in developed areas with sophisticated wastewater treatment plants results in the potential for competitive phosphorus trade in Europe and the United States also.

Recovered phosphorus is considered as the only source in the third scenario and with this only 38% of the global agricultural demand can be met. Because compost pellets, which due to their low P-density are far more expensive per tonne phosphorus than other products, the market prices for phosphorus are driven upwards in this scenario. This is a result of the model economics, where the different commodities (struvite vs. compost pellets) are treated as products acting on the same market - discriminated only based on their phosphorus content. When struvite producers observe consumers buying expensive compost pellets due to the depletion of struvite suppliers, the intial struvite sellers will adjust their prices upwards forcing consumers to pay pay more for the same amount for P. The inverse would be true also if agricultural consumers observed cheaper trades occurring among other actors. They would then demand lower prices from their producer or switch producer all together, both resulting in lower market prices.

4 Discussion

Several assumptions and simplifications have been made in this study that may have implications on its results. Inaccuracies in assessing the urban and livestock production potentials due to generalization of throughput figures, the lack of consideration for trans-Atlantic trade, the *as-the-crow-flies* distance method, assumptions of free trade, and other economic simplifications, all possibly contribute to errors in market price determination and patterns of trade flow. Most scrutiny of the results may be directed to assumptions on technological potential of recovery. The technological potential is assessed through the dataset *on urban population with access to improved sanitary facilities* – where improved facilities are defined as those designed to hygienically separate excreta from human contact. These may include anything ranging from pit latrines to flushed piped systems. A country's scoring in this dataset is then used as an indicator for the state of sanitary development in that country. Struvite precipitation from digestor liquor is assumed to be the technology appropriate for the highest scoring countries (>90% access). However, there is no guarantee that struvite precipitation from anaerobic digestor liquor is possible for nodes in these countries, seeing as by definition *improved sanitary facilities* 100% access may indicate that 100% of the urban population has access to a pit latrine. Even if information on the wastewater treatemeant infrastructure was known at all locations, then the phosphorus recovery efficiency from these rich sidestreams is still likely vary due to differences in phosphorus concentration of the influent. In summary, large uncertainties in the feasability to recover arise from the generalised technological assessment carried out. The assumptions are partially justified by the global and explorative nature of this study on potentials.

Despite the lack of studies on the global *economic potential* for recovery to compare results with, the results on *total potentials* and struvite pricing are well aligned to those of other studies. Above we determined that 3.7 [Mt a^{-1}] of phosphorus is maximally recoverable from wastewater, satisfying 20% of the reported 18.52 [Mt a^{-1}] agricultural demand (Heffer and Prud'homme, 2016), and 22% of determine agricultural demand (16.81 [Mt a^{-1}] for 2015). Smil (2000) found 3 [Mt/year] potentially recoverable, which would account for 20-25% of the global agricultural demand. Extrapolating Smil's (2000) figure proportionally with a population growth of 1.22% per year would result in a potential urban production of 3.6 [Mt/year] in 2015, a less than 3% difference from the potential reported. Mihelcic et al. (2011), through a study on diets and phosphorus excretion, concludes that the phosphorus excretion rates per individual can vary as much as from 0.18 P [kg a^{-1}] in the Democratic People's Republic of Congo, to 0.73 P [kg a^{-1}] in Israel. This confirms that our 'Western' approximation for phosphorus excretion of 0.77 P [kg a^{-1}] is on the global high end. For 2009, nonetheless, Mihelcic et al. (2011) determined that 3.4 P [Mt a^{-1}] of human waste produced could account for 22% of the 15 [Mt a^{-1}] of global phosphorus demand. These values are in good agreement with 3.7 P [Mt a^{-1}] urban waste and 16.8 P [Mt a^{-1}] phosphorus demand estimated by this study, yielding a 20% maximum potential satisfaction of global demand through human recovered waste in 2015. Koppelaar and Weikard (2013) estimated the potential of use reduction and recycling measures on the global phosphorus balance for 2009. In this balance, the phosphorus loading of human excreta amounts to 4.2 P [Mt/year], which is 25% of their 16.7 P [Mt a^{-1}] agricultural demand. They also estimated total domestic animal manure production 28.3 [Mt a^{-1}] of P. This is distinclty higher than this study's 17.11 P [Mt/year] livestock P production. This study limits livestock production to only that of cattle, swine and poultry excreted phosphorus, with recovery rates of 75-85%, and a cattle pasture period of 180 days during which excreted phosphorus is returned directly to fields and recovery is not possible. Provided the indistinction between beef and dairy cattle in the population density map, and the significant difference of phosphorus excretion rates of both beef and dairy cattle, it is not unlikely that the phosphorus production rate of all cows is in total much higher than currently approximated in this study. Koppelaar and Weikard's (2013) results would suggest an even greater potential for the recovery of livestock excreted phosphorus than the otherwise conservative estimate produced in this study.

The model estimates struvite *production costs* ranging from 0 to 560 [\$ t^{-1}], variable with the nature and location of the recovery site. Phopshorus *market prices* instead are determined to range from 273 to 391 [\$ t^{-1}] over the different years modelled for in a market with rock phosphate products. The supply deficit resulting from a scenario without rock phosphates, would drive these sale prices upwards to a range of 570 to 955 [$ t^{-1}]. These costs and prices are difficult to compare, as no found study has evaluated the economic potential of recovery at global scale. Instead, there exist case-studies on the feasibility for phosphorus recovery at specific sites. Ueno and Fujii (2001) observed that struvite obtained from wastewater in Japan is sold to fertilizer companies at rates of 300 [$ t^{-1}]. A market study by Münch and Barr (2001) revealed that struvite can be sold in Australia for between 220 and 370 [$ t^{-1}]. Shu et al. (2006), however, estimated that the market price of struvite is around 550 [$ t^{-1}]. Based on fertilizer market estimation, Dockhorn (2009) estimated far higher prices than those mentioned before, and valued recovered struvite at 900 [$ t^{-1}]. Dockhorn's high recovered product prices are approached in the model by the 2015 struvite market price, 955 [$ t^{-1}], for a market scenario with no rock phosphate competition and a severe P supply deficit. It appears that the model determined price range for global struvite production covers the spectrum of different production costs as determined in various different other studies.

5 Conclusion

Despite simplifying assumptions, the developed model creates realistic trade networks for different phosphorus supply scenarios, for different prices, at subnational resolution. However, the credibility of model outputs are only supported by an accurate simulation of DAP prices when run for a mine supply scenario because data and/or other studies on the purely hypothetical nature of global trade in sustainably recovered P is lacking.

The calculated total potential contribution of recovered phosphorus to the agricultural demand matched the conclusions of various other studies. In range with results by Smil (2000), Mihelcic et al. (2011), and Koppelaar and Weikard (2013), this study revealed that recovery of all (2005) human excreted phosphorus can potentially accommodate 22% of the determined, total agricultural phosphorus demand. Additionally, 89% of the global agricultural demand can potentially be satisfied through the recovery of phosphorus from all cattle, poultry and swine populations. More realistically limiting phosphorus recovery only to centers of high human and livestock population density, only 63% of the total agricultural demand can be met.

Considering economic variables, however, it is estimated that in a 2015 market that also offers cheaper rock based fertilizer alternatives, only 0.13 [Mt a^{-1}], or 0.8% of agricultural phosphorus demand can be competitively accommodated. In a market with no rock based alternatives, 38% of the agricultural demand can be met by recovering phosphorous from livestock and urban centres. This supply deficit will result in very high phosphorus prices. For both scenarios, maps reveal that this recovery is especially feasible in densely populated cities that lie in close proximity to areas of intensive agriculture, and that are situated far from large P-mines. Particularly Asia shows potential for economically competitive phosphorus recovery from wastewater. With struvite as a byproduct for reducing scaling maintenance and sludge handlings costs, trade in Europe and the Unites States also shows a high potential. The production and transportation cost per tonne P for compost pellets from source-separated faecal matter and livestock manure is high due to the relatively low phosphorus content. These products can hardly compete in the international phosphorus market and drive prices upwards when the demand for P is severe, e.g. when rock phosphate products are absent.

Recognizing that there is no single solution for solving phosphorus pollution and insecurity (Cordell and White, 2011), a reassessment of how we use and treat wastewater may provide an important contribution. The recovery of phosphorus from wastewater will become more appealing as populations grow and urbanize and phosphorus reserves deplete, and it is therefore important that more global economic assessments are done to determine how the widespread implementation of phosphorus recovery technologies can be stimulated, and to what extent these can be accommodated in the changing sanitation paradigm. Until then, current and future cases where phosphorus recovery is implemented will serve as prime examples from which governments can learn how to regulate phosphorus recovery in such a way that maximum benefits are achieved for both the environment and the urban community, as well as the livestock and agricultural sectors.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-176
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 10 April 2018

References

Arrow, K. J. and Debreu, G.: Existence of an Equilibrium for a Competitive Economy, Econometrica, 22(3), 265–290 [online] Available from: http://links.jstor.org/sici?sici=0012-9682%28195407%2922%3A3%3C265%3AEOAEFA%3E2.0.CO%3B2-B (Accessed 11 October 2017), 1954.

Barker, J. C., Hodges, S. C. and Walls, F. R.: Livestock Manure Production Rates and Nutrient Content, , 1–4, 2001.

Bjorn Vinnerås: Faecal separation and urine diversion for nutrient management of household biodegradable waste and wastewater, J. Biosci., 5(2), 29–50, 2001.

Breeuwsma, A. and Silva, S.: Phosphorus Fertilisation and Environmental Effects in The Netherlands and the Po Region (Italy), 1992.

CBS (Centraal Bureau voor de Statistiek): Dierlijke mest en mineralen 2013, Centraal Bureau voor de Statistiek, The Hague. [online] Available from: https://www.cbs.nl/-/media/imported/documents/2014/49/2014-dierlijke-mest-en-mineralen-2013-pub.pdf, 2014.

Center for International Earth Science Information Network - CIESIN - Columbia University: Gridded Population of the World, Version 4 (GPWv4): Population Density, [online] Available from: http://dx.doi.org/10.7927/H4NP22DQ (Accessed 1 May 2016), 2016.

Corcoran, E., Nellemann, C., Baker, E., Bos, R., Osborn, D. and Savelli, H.: Sick Water? The Central Role of Wastewater Management in Sustainable Development, United Nations Environment Programme., 2010.

Cordell, D. and White, S.: Peak phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security, Sustainability, 3(10), 2027–2049, doi:10.3390/su3102027, 2011.

Cordell, D., Schmid-Neset, T., White, S. and Jan-Olof, D.: Preferred Future Phosphorus Scenarios: A Framework For Meeting Long-Term Phosphorus Needs for Global Food Demand, Int. Conf. Nutr. Recover. from Wastewater Streams, 2009.

Dockhorn, T.: About the Economy of Phosphorus Recovery, Int. Conf. Nutr. Recover. from Wastewater Streams, 2009.

Egle, L. A.: Doctoral Thesis Phosphorus recovery from municipal wastewater Dissertation Phosphorrückgewinnung aus kommunalem Abwasser., n.d.

EPA (United States Environmental Protection Agency): Nutrient Control Design Manual, The Cadmus Group, Inc, Washignton, D.C., 2010.

FAO (Food and Agriculture Organisation) and IFA (International Fertilizer Industry Association): Fertilizers and Their Use: A pocket guide for extension officers, Rome, Italy., 2000.

Gilmour, D., Blackwood, D., Comber, S. and Thornell, A.: Identifying human waste contribution of phosphorus loads to domestic wastewater, Preceedings 11th Int. Conf. Urban Drainage, Held Edinburgh, Scoltand, UK, 1–10, 2008.

Heffer, P.: Assessment of Fertilizer Use by Crop at the Global Level., 2009.

IndexMundi: Index Mundi Commodity Price Indices, [online] Available from: http://www.indexmundi.com/commodities/ (Accessed 1 May 2017), 2017.

van Kauwenbergh, S.: World phosphate reserves and resources, Fertil. Outlook Technol. Conf., 1–18, doi:3, 2010.

Koppelaar, R. H. E. M. and Weikard, H. P.: Assessing phosphate rock depletion and phosphorus recycling options, Glob. Environ. Chang., 23(6), 1454–1466, doi:10.1016/j.gloenvcha.2013.09.002, 2013.

Masayuki Hara: Fertilizer Pellets Made from Composted Livestock Manure, Mie Prefect. Sci. Technol. Promot. Cent. [online] Available from: http://www.fftc.agnet.org/library.php?func=view&id=20110801154610 (Accessed 12 January 2018), 2001.

Mihelcic, J. R., Fry, L. M. and Shaw, R.: Global potential of phosphorus recovery from human urine and feces., Chemosphere, 84(6), 832–9, doi:10.1016/j.chemosphere.2011.02.046, 2011.

Münch, E. V and Barr, K.: Controlled struvite crystallization for removing phosphorus from anaerobic digester side stream, Water Res., 35(1), 151–159, 2001.

Oenema, O. and Roest, C. W. J.: Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands, Water Sci. Technol., 37(3), doi:10.1016/S0273-1223(98)00052-3, 1998.

Oenema, O., Oudendag, D. and Velthof, G. L.: Nutrient losses from manure management in the European Union, Livest. Sci., 112(3), 261–272, doi:10.1016/j.livsci.2007.09.007, 2007.

Pande, S. and Savenije, H. H. G.: A sociohydrologicalmodel for smallholder farmers in Maharashtra, India, , 7503–7512, doi:10.1002/2016WR018977.Received, 2016.

Quantum GIS Development Team: Quantum GIS Geographic Information System 2.14, Open Source Geospatial Found. Proj. [online] Available from: http://qgis.osgeo.org, 2017.

Robinson, T. P., William Wint, G. R., Conchedda, G., van Boeckel, T. P., Ercoli, V., Palamara, E., Cinardi, G., D'Aietti, L., Hay, S. I. and Gilbert, M.: Mapping the global distribution of livestock, PLoS One, 9(5), doi:10.1371/journal.pone.0096084, 2014.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, R. J., Izac, A. N., Mokwunye, A. U., Kwesiga, F. R., Ndiritu, C. G. and Woomer, P. L.: Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital Pedro,

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-176
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 10 April 2018

Replenishing soil Fertil. Africa, (SSSA Special Publication 51), 1–47, doi:10.2136/sssaspecpub51.c6, 1997.

Schoumans, O. F., Bouraoui, F., Kabbe, C., Oenema, O. and van Dijk, K. C.: Phosphorus management in Europe in a changing world, Ambio, 44(2), 180–192, doi:10.1007/s13280-014-0613-9, 2015.

Shu, L., Schneider, P., Jegatheesan, V. and Johnson, J.: An economic evaluation of phosphorus recovery as struvite from digester supernatant, Bioresour. Technol., 97(17), 2211–2216, doi:10.1016/j.biortech.2005.11.005, 2006.

Sims, J. T., Edwards, A. C., Schoumans, O. F. and Simard, R. R.: Integrating soil phosphorus testing into environmentally based agricultural management practices, J. Environ. Qual., 29, 60–71, 2000.

Sivapalan, M., Savenije, H. H. G. and Blöschl, G.: Socio-hydrology: A new science of people and water, Hydrol. Process., 26(8), 1270–1276, doi:10.1002/hyp.8426, 2012.

Smil, V.: Phosphorus in the environment: Natural flows and human interferences, Annu. Rev. Energy Environ., 25, 53–88, doi:10.1146/annurev.energy.25.1.53, 2000.

Steduto, P., Hsiao C., T., Fereres, E. and Raes, D.: FAO Irrigation and Drainage Paper: Crop Yield Response to Water, Food and Agriculture Organization of the United Nations (FAO), Rome., 2012.

Steen, I.: Management of a non-renewable resource, Phosphorus and potassium, (217), 25–31 [online] Available from: http://cat.inist.fr/?aModele=afficheN&cpsidt=2380873 (Accessed 24 March 2016), 1998.

Ueno, Y. and Fujii, M.: Three Years Experience of Operating and Selling Recovered Struvite from Full-Scale Plant, Environ. Technol., 22(11), 1373–1381, doi:10.1080/09593332208618196, 2001.

USGS (United States Geological Survey): World phosphate mines, deposits, and occurrences, [online] Available from: https://mrdata.usgs.gov/phosphate/, 2002.

USGS (United States Geological Survey): Mineral Commodity Summary Phosphate Rock, Washington, D.C. [online] Available from: https://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/phospmcs06.pdf, 2007.

USGS (United States Geological Survey): Mineral Commodity Summary Phosphate Rock, Washington, D.C. [online] Available from: https://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/phospmcs06.pdf, 2010.

Van Vuuren, D. P., Bouwman, A. F. and Beusen, A. H. W.: Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion, Glob. Environ. Chang., 20(3), 428–439, doi:10.1016/j.gloenvcha.2010.04.004, 2010.

WHO/UNICEF JMP (Joint Monitoring Programme): Percent of Urban Population with Access to Improved Sanitation Facilities., 2015.

Wilsenach, J. A. A., Schuurbiers, C. A. H. A. H. and van Loosdrecht, M. C. M. C. M.: Phosphate and potassium recovery from source separated urine through struvite precipitation., Water Res., 41(2), 458–66, doi:10.1016/j.watres.2006.10.014, 2007.

World Bank: Population growth (annual %) | Data, [online] Available from: https://data.worldbank.org/indicator/SP.POP.GROW (Accessed 3 January 2018), n.d.

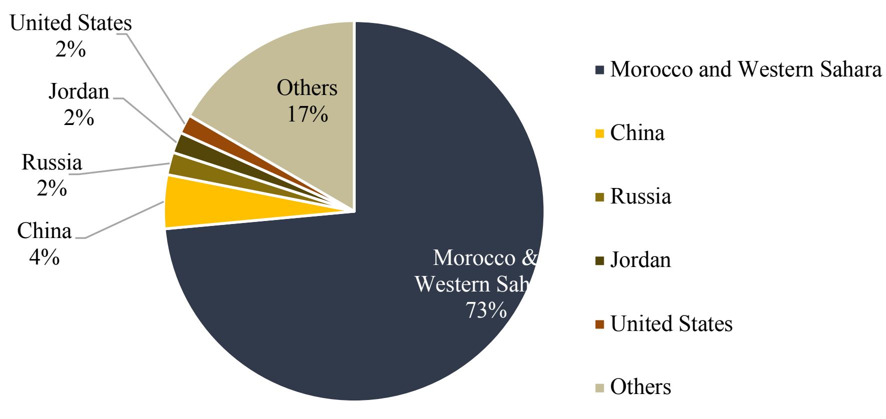

Figure 1. Estimated global phosphorus reserve distribution. The vast majority (73%) of estimated natural reserves lie in Moroccan and West-Saharan territories (USGS, 2017).

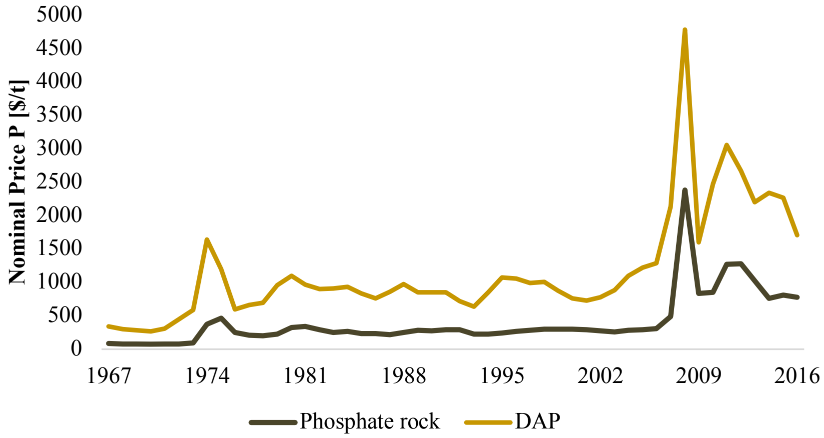

Figure 2. Nominal Phosphate rock and DAP price trends (IndexMundi, 2017). The rock phosphate and DAP price trend can be characterized as stable, gradually increasing, and vulnerable to market dynamics (i.e. the 2007 global economic recession).

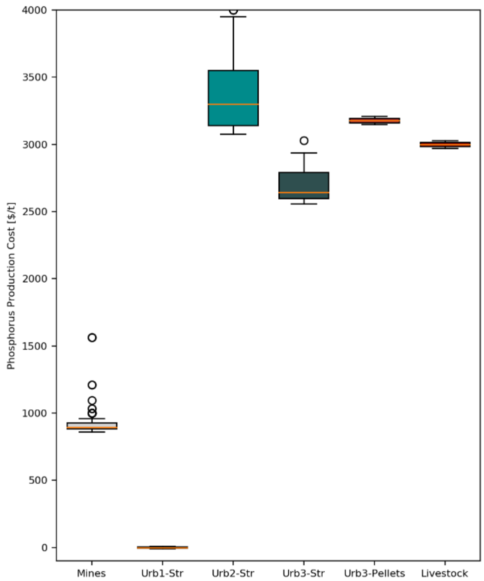

Figure 3. Minimum production costs per ton of recycled P for supply nodes. Urb1-Str shows the prices for struvite from WWTP in countries with highly developed sanitation systems (BNR), where the struvite is offered for free (excl. transport costs) because of the maintenance and sludge handling savings by controlled struvite precipitation; Urb2-Str, from nations with slightly less developed sanitation systems; Urb3-Str, of source-separated urine collection and struvite precipitation in nations with underdeveloped sanitation systems; Urb3-Pellets, the price per tonne P (0.1%) in urban compost pellets; and Livestock shows the price per tonne P in livestock pellets (0.1% P).

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-176
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 10 April 2018

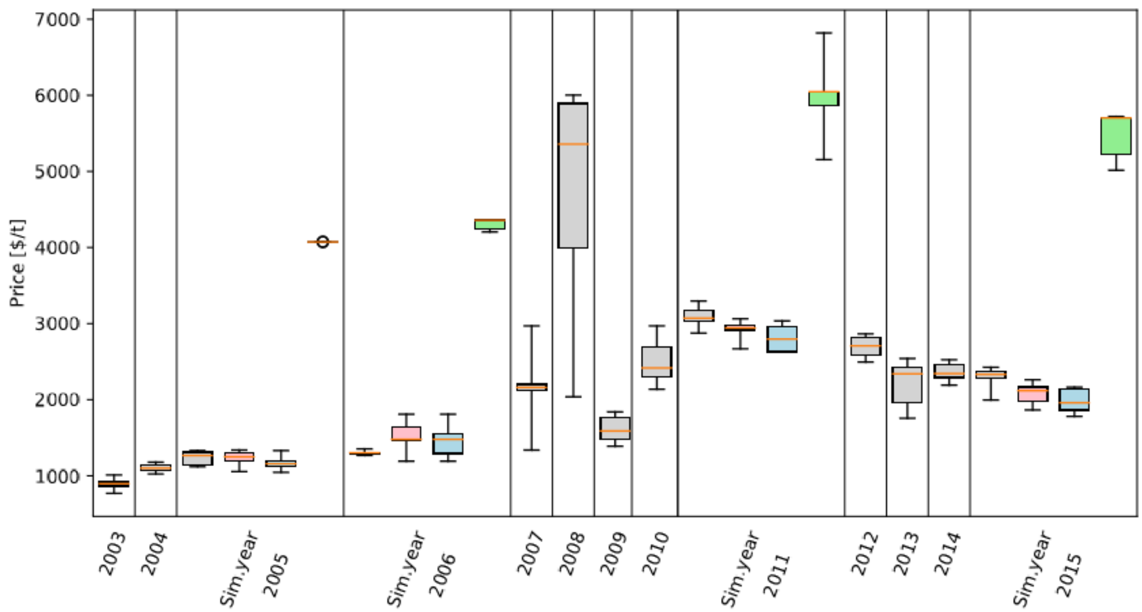

Figure 4. Plausible phosphorus price ranges at which trade can occur at global scale for different years: observed prices (grey) versus modelled scenarios (Sc. 1, pink; Sc. 2, blue; Sc. 3, green). The ends of the whiskers on the grey boxes for the observed prices represent the maximum and minimum prices for DAP that year, the box itself shows the upper and lower quartiles for that data and the orange line indicates the median. For the modelled scenario the whisker-ends show the maximum and minimum prices as approximated by the model, and the box the most likely price range. Noticeable is that the price determinations for the current mines only scenario are in close proximity with observed price ranges. Scenario 2 and 3 are hypothetical scenarios and therefore cannot be compared. Nevetheless they show predictable and realistic behaviour.

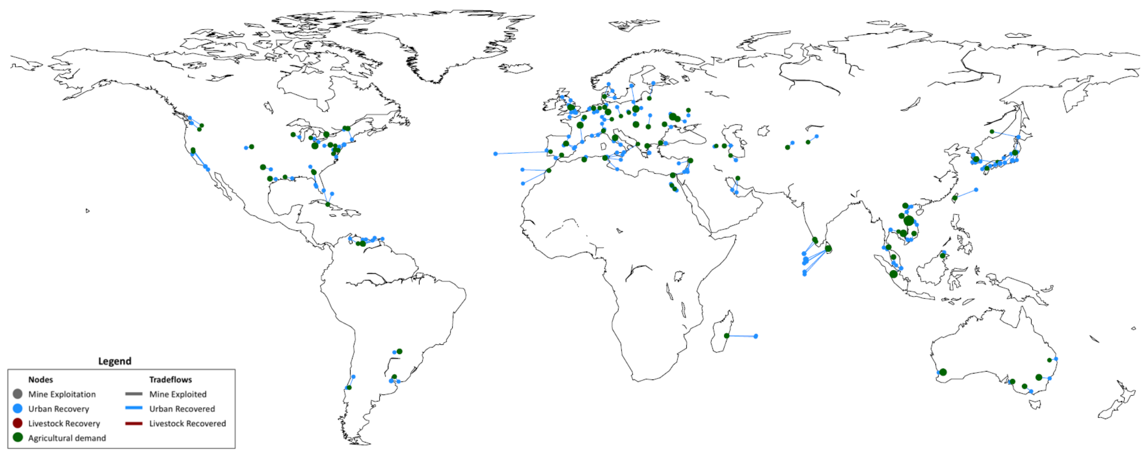

Figure 5. Phosphorus trade network for trade in both conventional and recycled P (scenario 2) but showing only sustainable trade flows. Optimal trade occurs at a phosphorus market price of 1,950 [$ t^{-1}] with 16.81 [Mt] being traded in total, of which 0.13 [Mt] is traded sustainably (0.8% of total demand).

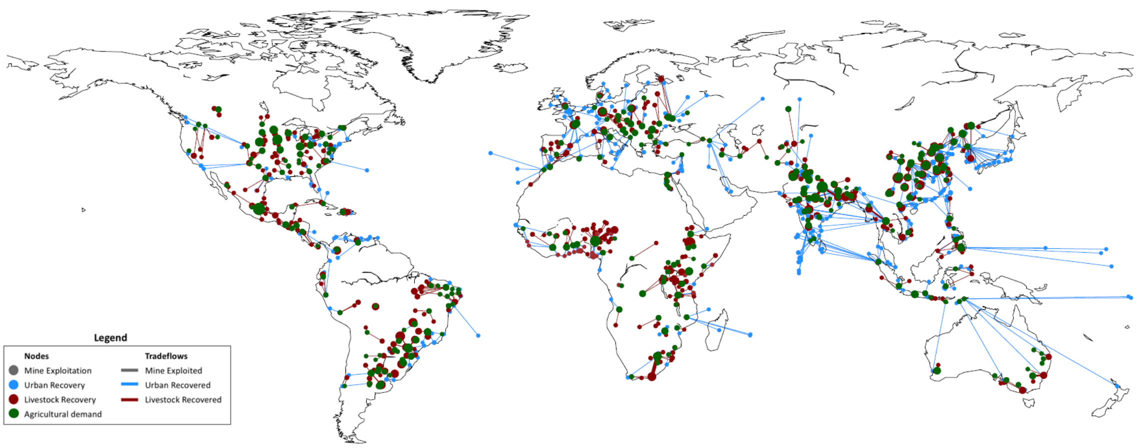

Figure 6. Phosphorus trade network for trade in recycled P only (scenario 3) at determined phosphorus market prices of 5,700 [$ t^{-1}] with 6.42 [Mt] being traded. All of this trade is sustainable but is only able to accommodate 38% of demand.

Continental Phosphorus Budgets

	Livestock Raster (fig. S2a) [Mt P]	Livestock Node [Mt P]	Human Raster (fig. S2b) [Mt P]	Urban Node [Mt P]	Agri. Dem. Raster (fig. S2c) [Mt P]
Asia	6.75	-	2.29	-	9.30
North America	1.98	-	0.31	-	3.24
Europe	1.93	-	0.40	-	1.75
Africa	2.55	-	0.53	-	2.46
South America	3.56	-	0.22	-	2.13
Oceania	0.10	-	0.00	-	0.00
Australia	0.26	-	0.01	-	0.24
World	17.11	10.47	3.75	1.73	19.11

Table 1. Approximate continental phosphorus budgets associated to maps.

Price Determinations

		Scenario 1 [$ t^{-1}]	Scenario 2 [$ t^{-1}]	Scenario 3 [$ t^{-1}]
Determined Phosphorus Price	**Min.**	1,900	1,900	5,100
	Opt.	2,119	1,955	5,700
	Max.	3,000	3,000	5,700
Max. Amount Traded	**[Mt]**	16.81	16.81	6.42
	[%]	100%	100%	38%

Table 2. Price ranges and amounts traded per scenario for 2015. The minimum price represents the lower boundary of the determined market price range, the maximum its upper boundary, and the optimum represents the model approximated economic-optimal, most realistic, actual price. The 'maximum amount traded' shows how much percent of the total agricultural demand is accommodated in each supply scenario.