Supplementary Material

Supplementary Text

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 (fig. A).

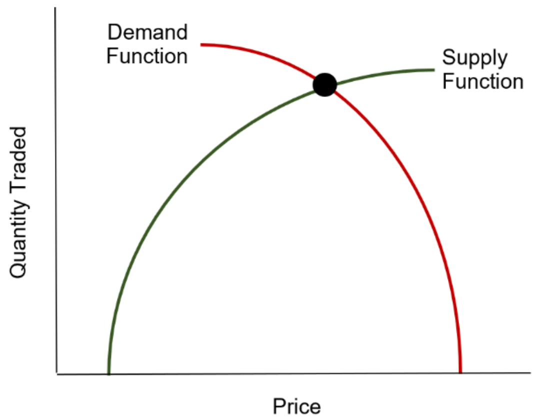


Figure A. Conceptualization of supply-demand curves. The interception point of both curves marks an approximation for the price equilibrium.

However, good nutrient management leads farmers not to purchase more phosphorus than the optimal amount that is required for their crops. As such, it is assumed that farmers do not over-fertilize (buy more fertilizers than they need for optimal yield) when fertilizer prices are extremely low. Therefore the phosphorus trade will be limited by maximum global demand (Q_m) for price, P. This assumption would flatten the demand curve beyond the price at which the market is saturated. The created supply-demand curves for the network will deviate further from the traditional curves when including transport cost. Transportat cost cis determined based on the distance between two trading nodes and therefore cannot be determined for nodes without a trade partner (i.e. not partaking in trade). The curves created for the network are therefore limited to using data only of those nodes partaking in trade.

To exemplify this consider figure A, where three production nodes and three demand nodes populate a hypothetical network. The production nodes have a minimum per unit production costs ($P_1 < P_2 < P_3$) and specific quantities (Q_1, Q_2, *and* Q_3) to sell. The demand nodes have maximum prices they are willing to pay ($P_4 < P_5 = P_6$) for their quantities (Q_4, Q_5, *and* Q_6) to buy. The transportation costs ($T_{(i,n)}$) for all production nodes are lowest to demand node D4, highest to D6 and intermediate to D5 ($T_{(i,4)} < T_{(i,5)} < T_{(i,6)}$). This results in the cheapest, and therefore first, trade occurring between S1 and D4, as: $P1+T_{(1,4)} << P_i+T_{(i,n)}$ (line 1, Figure B).

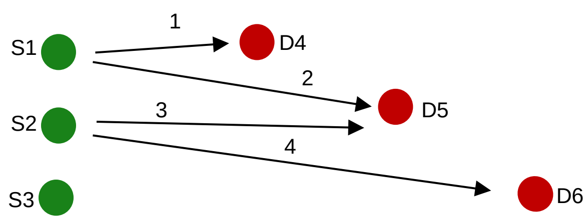


Figure B. Network of demand and supply nodes. Arrows with numbers indicate trade order, including transportation costs.

For this first trade, quantity Q4 is smaller than Q1 and therefore the amount traded is equal to the node's entire demand, Q4, etc. The next cheapest trade follows until the entire demand is satisfied or supply is depleted. In this hypothetical network the entire demand can be satisfied by the first two production nodes. The third supply node is therefore not involved in trade. Since the transport component of the price cannot be determined for this node, it is disregarded in the creation of the supply-demand curve. Executing this procedure successively for all nodes, in the example network, and plotting the prices inclusive of transportation cost with the networks cumulative quantity traded yields figure C. The cumulative quantity traded for each individually bargained price is summarized in table A.

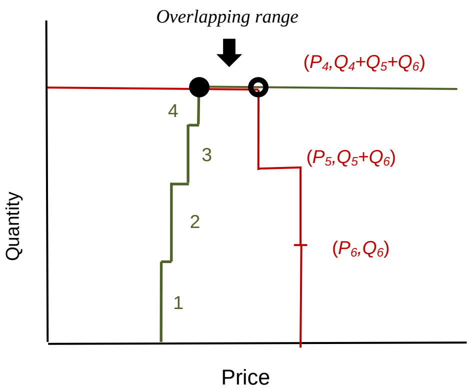


Figure C. Adapted supply (green) and demand (red) curve, for six node network illustrated in Figure 12, including transportation cost component in price.

TRADE ORDER, PRICES AND QUANTITIES FOR EXAMPLE NETWORK

Trade Order	Node Pair (i,n)	Best 'hypothetical' Prices	Quantity Traded	Cumulative Quantity Traded
1	(1,4)	$P_1+T_{(1,4)}$	Q_4	Q_4
2	(1,5)	$P_1+T_{(1,5)}$	$Q_1- Q_5$	$Q_4 + Q_1 - Q_5$
3	(2,5)	$P_2+T_{(2,5)}$	$Q_2-(Q_1- Q_5)$	$Q_2 + Q_4 + Q_5$
4	(2,6)	$P_2+T_{(2,6)}$	Q_6	$Q_3 + Q_4 + Q_5$

Table A. Trade order, prices and quantities for node pairs for supply curve.

Where the supply and demand curves overlap, both consumers and producers are satisfied with the amount of phosphorus traded at those prices. This range is thus indicative of the range wherein the optimal market price will lie. A more precise estimate of the optimal price is made using information on the demand or supply nodes not partaking in trade. Depending on the total proportion of excess supply or demand (i.e. $\frac{Q1+Q2+Q3}{Q4+Q5+Q6}$) the optimal price will lie in the upper or lower half of the range. When the total supply is far greater than the total demand, then demand nodes are in power to bargain for cheaper prices. The opposite is true for when demand is greater than supply. As such, a more precise estimate of optimal market price can be made.

Optimum price determination from range

Unless the supply and demand curves intersect each other before the maximum total quantity that can be traded is reached, the optimum price is identified to lie between the prices at which the supply and demand curves reach maximum trade. The optimal price can be further differentiated from this (potentially large) range. Depending on the proportion of global phosphorus supply to demand, it is possible to determine whether the optimum price will lie in the upper or lower half of this range. When the total supply is far greater than the demand, then the demand nodes are in a stronger bargaining position, and are able to shift the prices downward in their favor. The opposite is true when the demand is far greater than the supply, then the supply nodes can shift the prices to the upper end of the spectrum, to their favor. By this premise, we can reduce the large range to either the top half or lower half. Depending on the slope of the supply curve as it meets the satisfiable demand, a large reduction in price may lead to only a minor reduction trade. Extending therefore the upper and lower boundaries to the price that allow for 95% of maximum trade, some small possible errors in accuracy or market flexibility are more appropriately accounted for. The models best-guess price lies in the middle of the final range.

Supplementary Figures

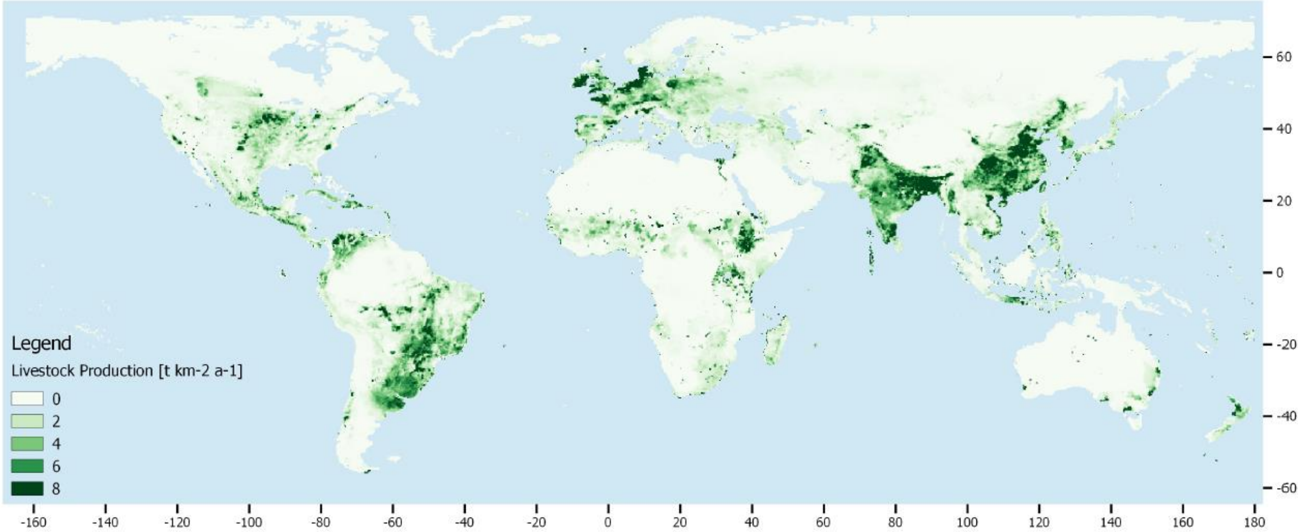


Figure S1a. Potential phosphorus recovery from bovine, swine and poultry livestock in tonnes per square kilometre for 2015.

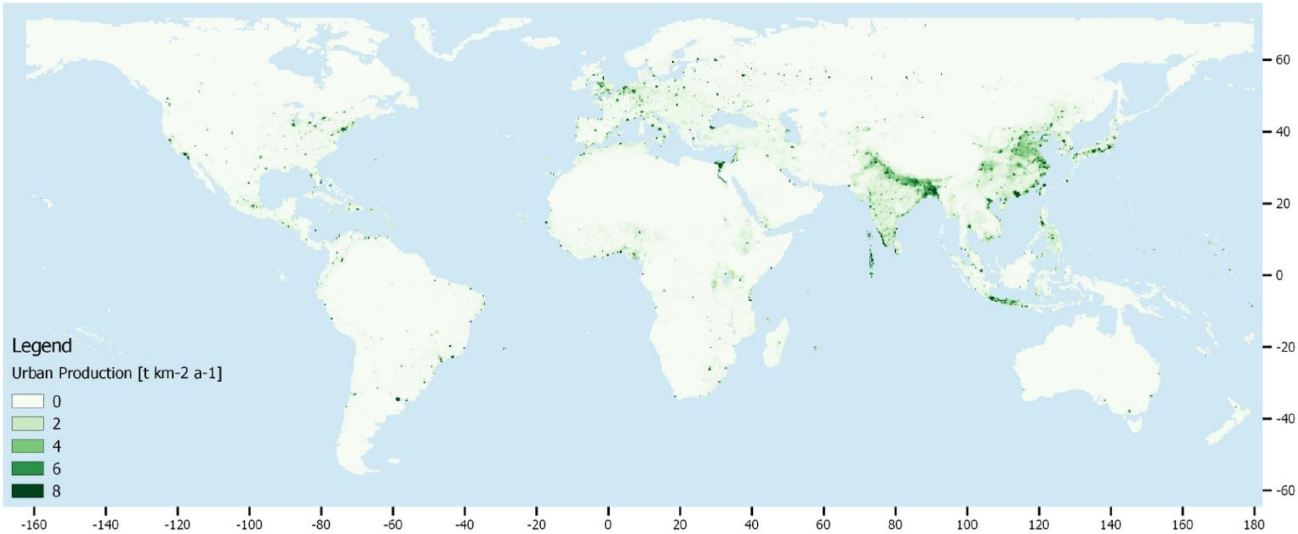


Figure S1b. Potential phosphorus recovery from human population in tonnes per square kilometre for 2015.

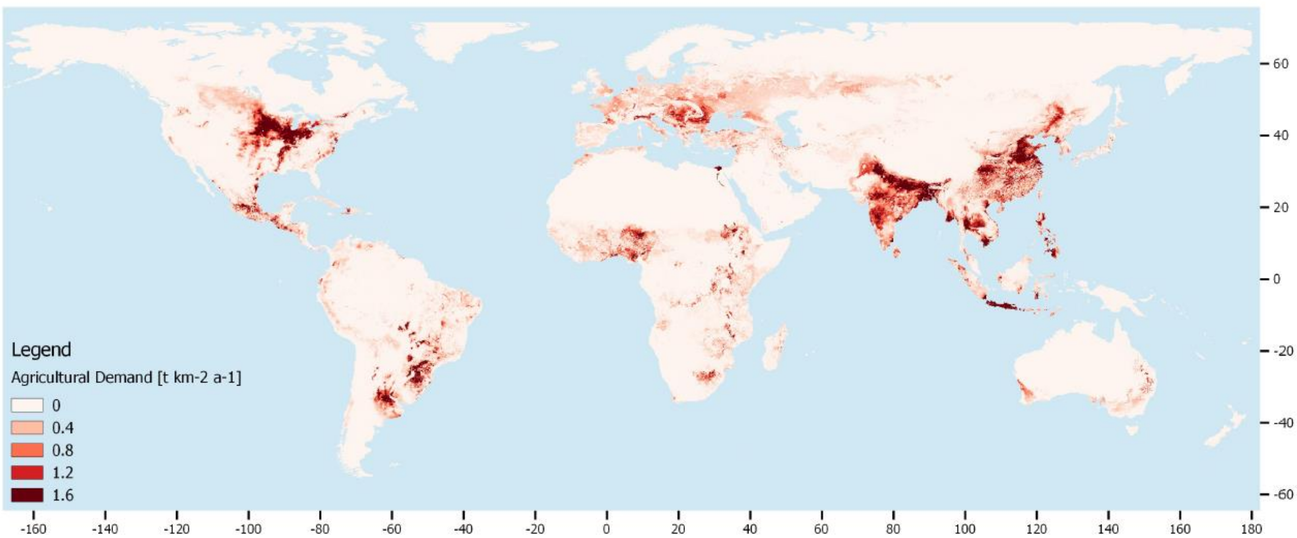
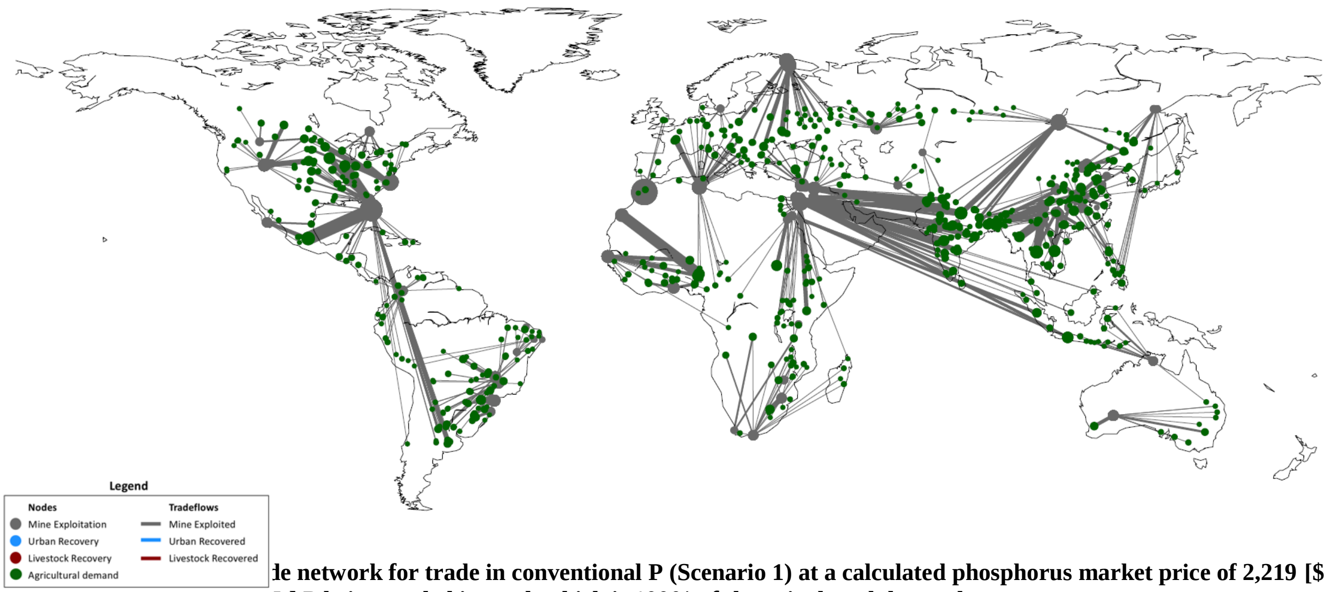


Figure S1c. Approximate, combined phosphorus demand for Maize, Wheat, Rice, Soybean, Sorghum and Potato in tonnes per square kilometre.



de network for trade in conventional P (Scenario 1) at a calculated phosphorus market price of 2,219 [$ t^{-1}]. This results in 16.81 [Mt] P being traded in total, which is 100% of th agricultural demand.

Supplementary Tables

Phosphorus Production Estimate Data

Population	Throughput (kg P)		Site	Author
Bovine (Dairy)	25		US	Barker et al., 2001
	17.16		NL	Blokland, Luesink, & Jongeneel, 2015
	17.9		NL	CBS, 2014
	20.8		US	Weiss & Wyatt, 2004
	9.6	(stabled period)	NL	CBS, 2014
Bovine (Beef)	11.7		NL	CBS, 2014
	13.3		US	Barker et al., 2001
	5.4	(stabled period)	NL	CBS, 2014
Poultry (layer)	1.2		US	Barker et al., 2001
	0.17		NL	CBS, 2014
Poultry (broiler)	0.6		US	Barker et al., 2001
	0.08		NL	CBS, 2014
Swine	4.1		US	Barker et al., 2001
	2.1		NL	CBS, 2014
Swine (sow)	6.4		NL	CBS, 2014
Human	0.77		UK	Gilmour et al., 2008
	0.2-0.7		Global	Mihelcic et al., 2011
	0.78		-	CRC, 2005
	0.7		US	Smil, 2000

Table S1. Annual phosphorus excretion rate by species, per head.

Crop Phosphorus Requirement Data

Crop	Ky [-]	Water req. [mm/harvest]	Growing Period [days]	P_2O_5 [kg/ha]	P_2O_5 [kg/ha]	P [kg/ha]
Maize	1.30	500-800	$80^{-1}80$	36-50	50	22
Wheat	0.55	450-650	$120^{-1}50$	27-60	40	15
Rice[1]	1.00	450-700	$90^{-1}50$	26-50	35	15
Soybean	0.90	450-700	$135^{-1}50$	35	35	15
Sorghum	0.90	450-650	$120^{-1}30$	20-40, 40-60	40	15
Potato	0.90	500-700	$105^{-1}45$	39-80	80	35

Table S2. Crop Data (FAO, n.d.; IFDC & UNIDO, 1998)

[1] Fageria, N.K. The Use of Nutrients in Crop Plants. Google books

Transportation Cost Parameters

Sea Transport Component Cost				Land Transport Component Cost			
Constant		**Value**	**Source**	**Constant**		**Value**	**Source**
P_b	[$ t^{-1}]	173	(World Scale, 2017)	P_d	[$ L^{-1}]	1.9	(IndexMundi, 2017)
E_W	[t d^{-1}]	30	(Počuča, 2006)	E_L	[L km^{-1}]	0.53	(Nylund and Erkkilä, 2005)
W_W	[t]	28,909	(Počuča, 2006)	W_L	[t]	60	
$\bar{V}_W$	[km d^{-1}]	622	(Počuča, 2006)	$\bar{V}_L$	[km h^{-1}]	80	-
C_F	[$ d^{-1}]	5,000	(Počuča, 2006)	L_c	[$ h^{-1}]	17	-
C_b	[kg t^{-1}]	3,130	(IMO, 2009)	C_d	[kg L^{-1}]	2.7	(IEEP, Ecologic, & Dias Soares, n.d.)

Table S3. Constants for transport cost determination equation (eq. 6)

Adjusted Parameters For Different Years

Parameter	Units	2005	2006	2011	2015	Source
Cost of RP production	[$ t^{-1}]	40	40	197	115	IndexMundi, 2017
Human Population	[h]	100%	101.2%	107.5%	113.2%	World Bank, n.d.
Livestock	[h]	100%	101.7%	111%	119%	FAO, n.d.
Crop Price Change	[$ t^{-1}]	146	156	229	210	IndexMundi, 2017
Diesel Fuel Price	[$ l^{-1}]	1.05	1.12	1.34	1.29	IndexMundi, 2017
Bunker Fuel Price	[$ t^{-1}]	173	231	485	614	World Scale, 2017
Agricultural Demand[2]	[MHa]	1.14	1.15	1.25	1.27	FAOSTAT, n.d.
Mine Production	[Mt]	147	142	198	241	USGS Min. Com. Summaries

Table S4. Parameter estimates for 2006, 2011 and 2015 simulations years such that they are consistent with corresponding figures reported in the mentioned sources.

[2] As Increase in Net Agricultural Production Index.