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Supplement of

Global phosphorus recovery from wastewater for agricultural reuse

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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).

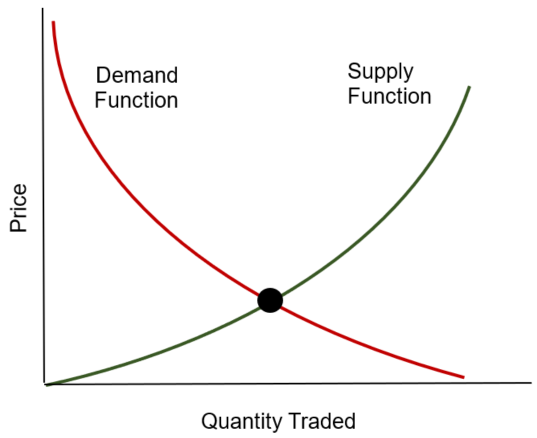


Figure A. Conceptualization of supply-demand curves. The interception point of both curves marks an approximation for the price equilibrium.

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 is 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: $P1+T_{(1,4)} \ll P_i+T_{(i,n)}$ (line 1, Figure B).

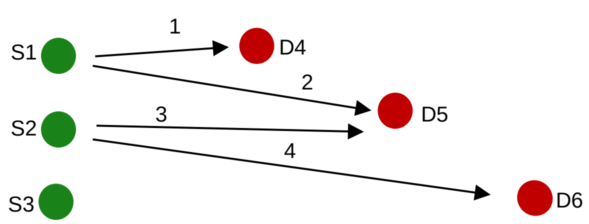


Figure B. Network of demand and supply nodes. Arrows with numbers indicate trade order, including transportation costs.

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.

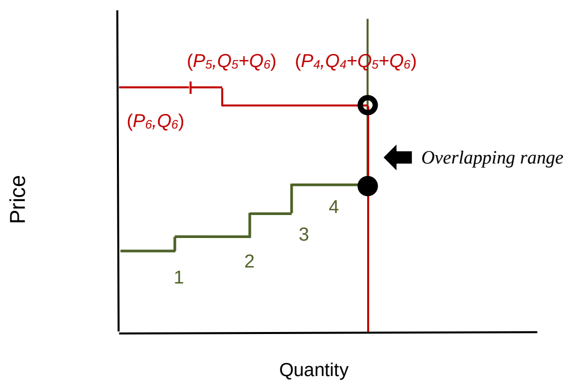


Figure C. Adapted supply (green) and demand (red) curve, for six node network illustrated in Figure 12, including transportation cost component in price.

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.

Results: Production 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.

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. Furthermore, the production and transportation cost per tonne P for compost pellets from source-separated faecal matter and livestock manure will be high due to the relatively low phosphorus content. These products are unlikely able to 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.

Supplementary Figures

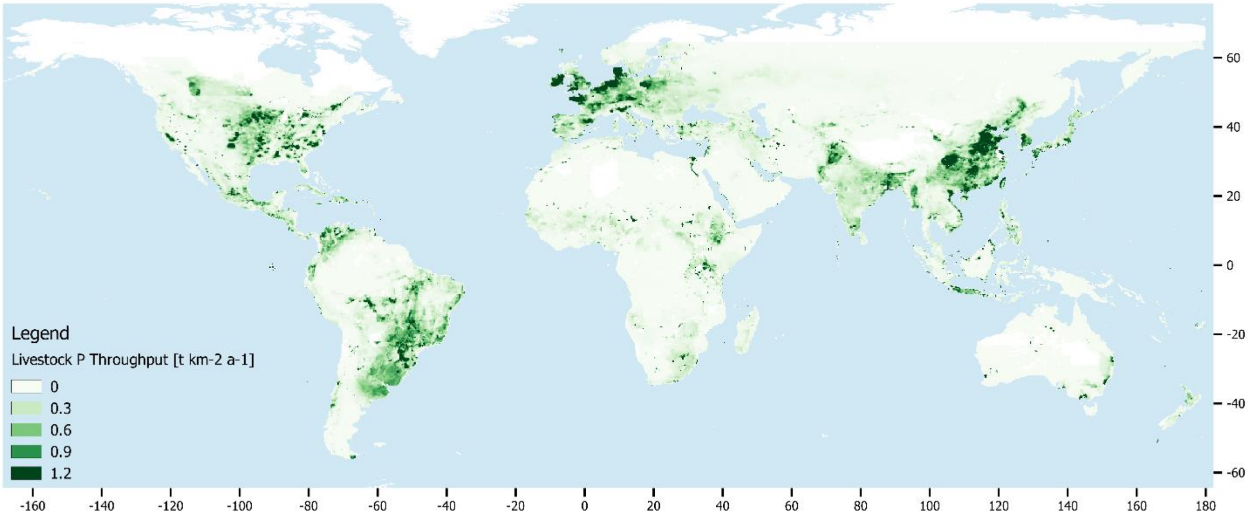


Figure S1a. Potential phosphorus recovery from bovine, swine and poultry livestock in tonnes per square kilometre.

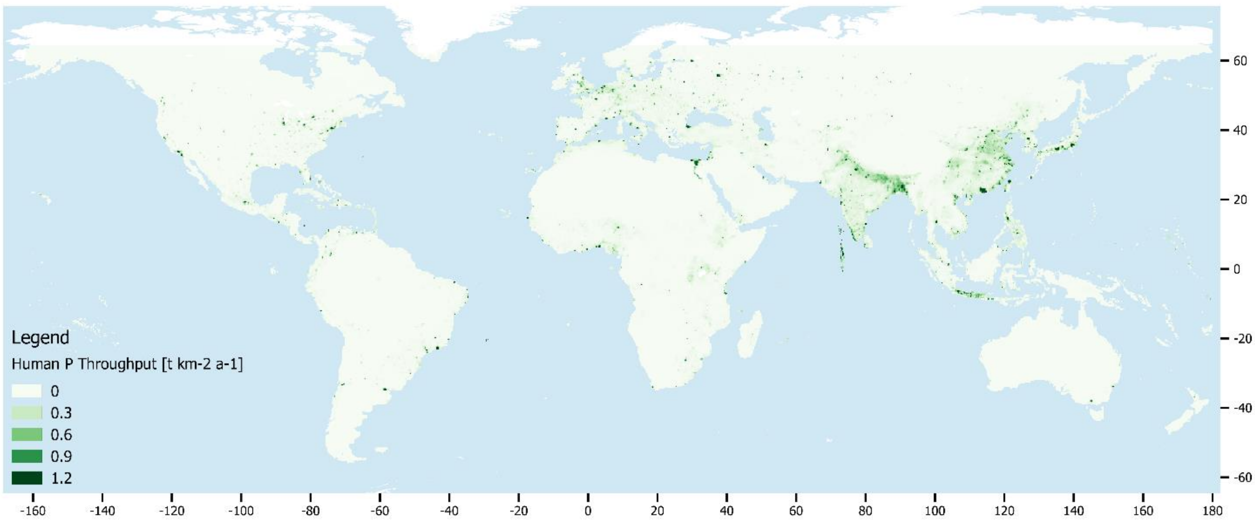


Figure S1b. Potential phosphorus recovery from human population in tonnes per square kilometre.

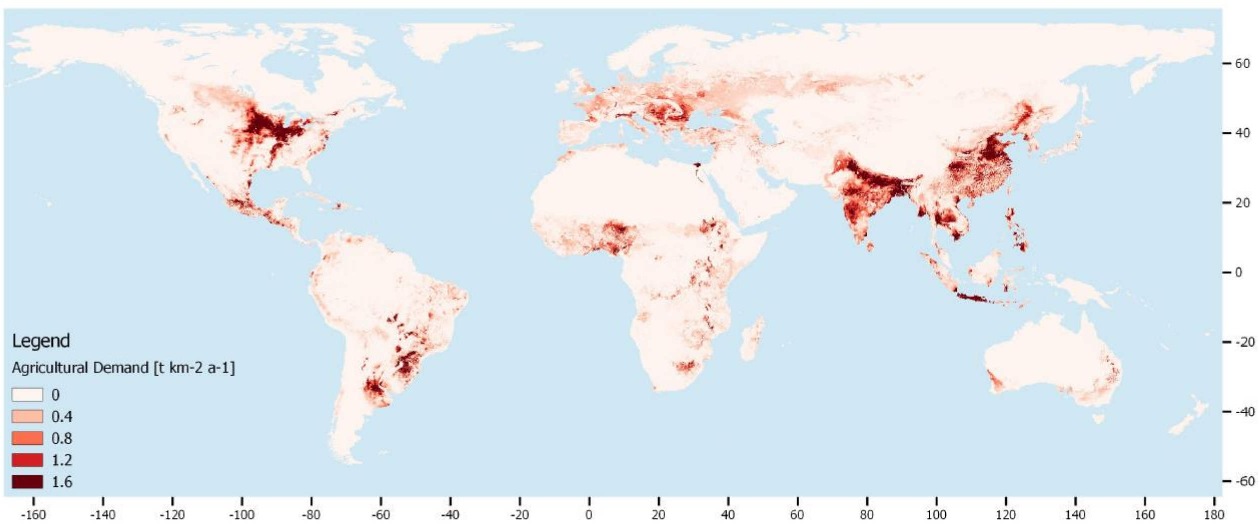


Figure S1c. Approximate, combined phosphorus demand for six major crops in tonnes per square kilometre.

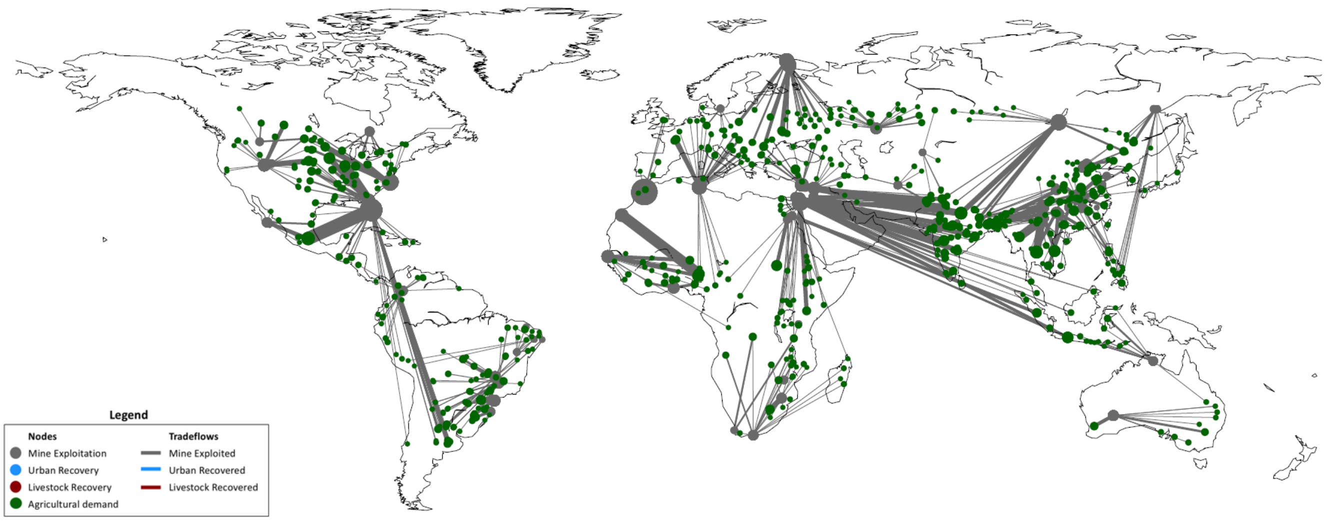
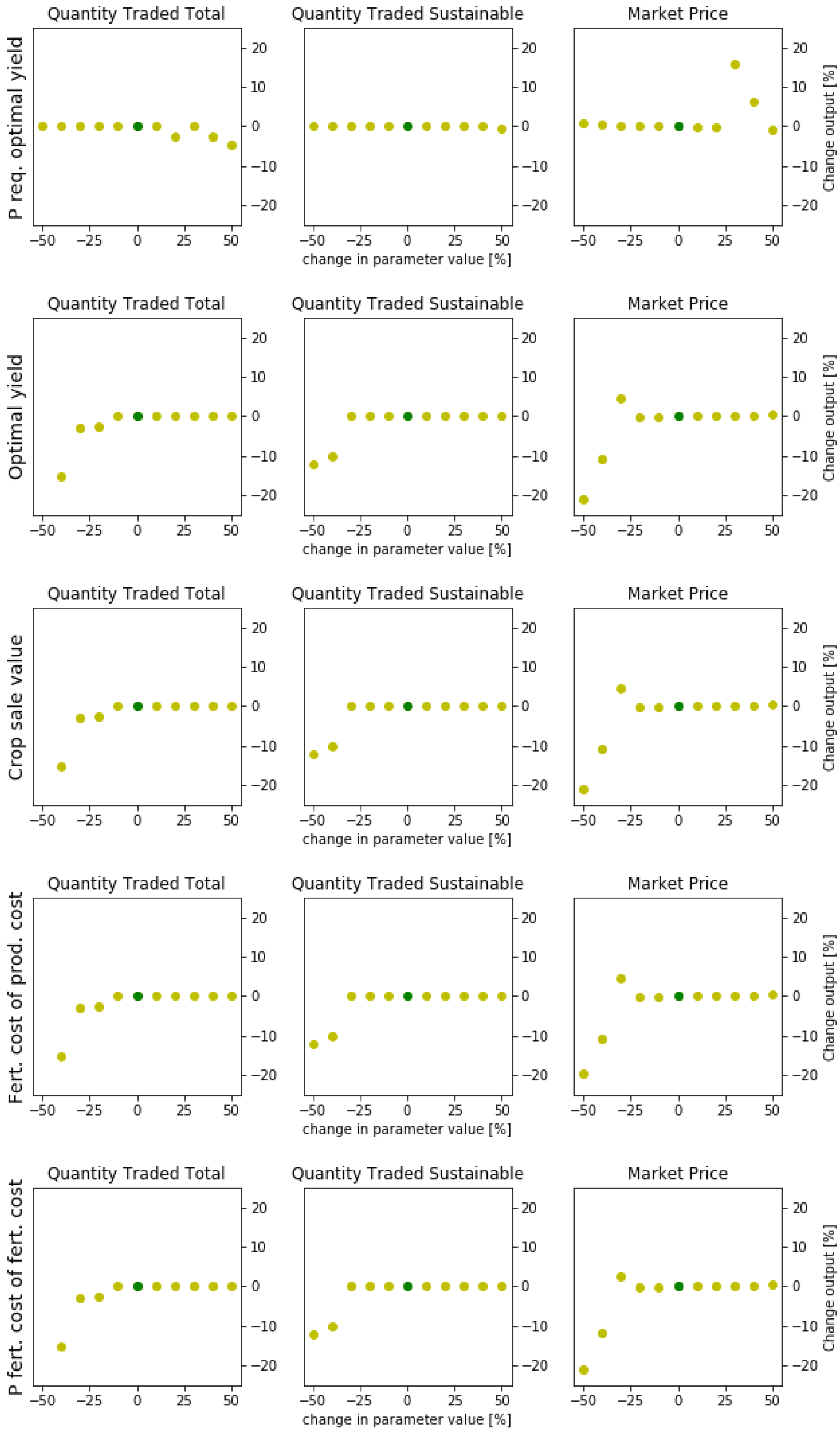


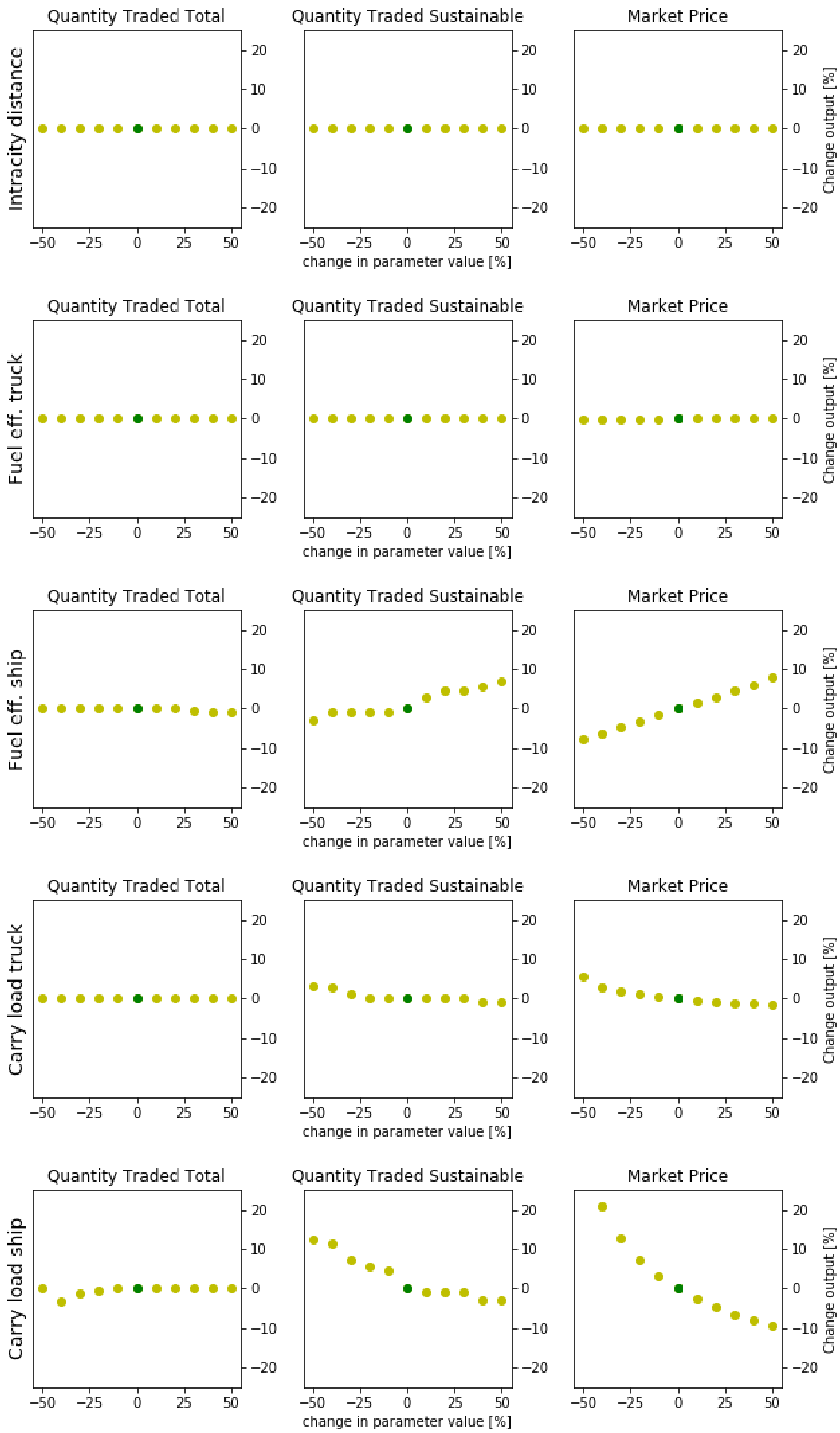
Figure S2. Phosphorus trade network for trade in conventional P (Scenario 1) at a calculated phosphorus market price of 2,155 [$ t^{-1}]. This results in 19.51 [Mt] P being traded in total, which meets 100% of the agricultural demand.

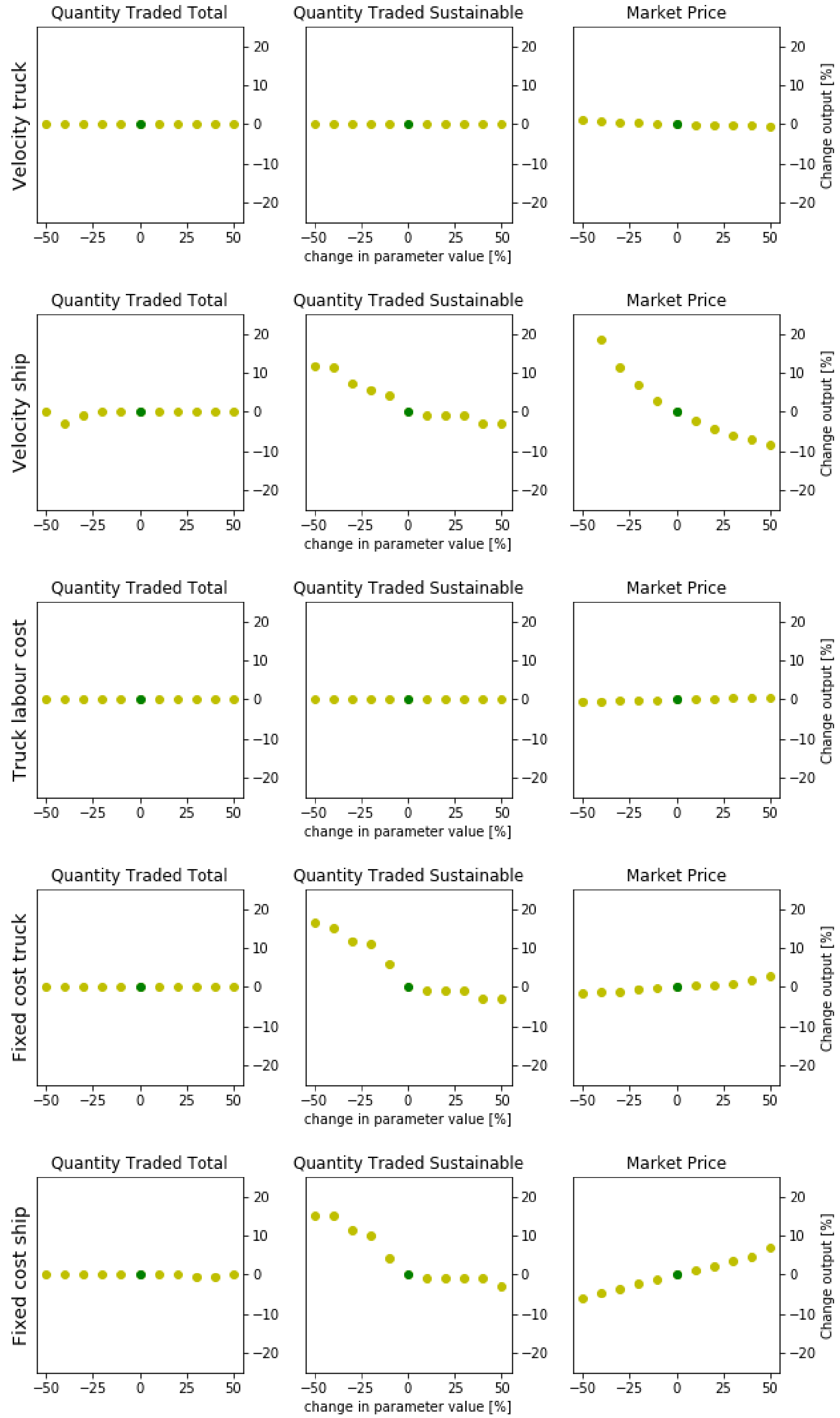
S3. Parameter Sensitivity Figures

Crop Parameters

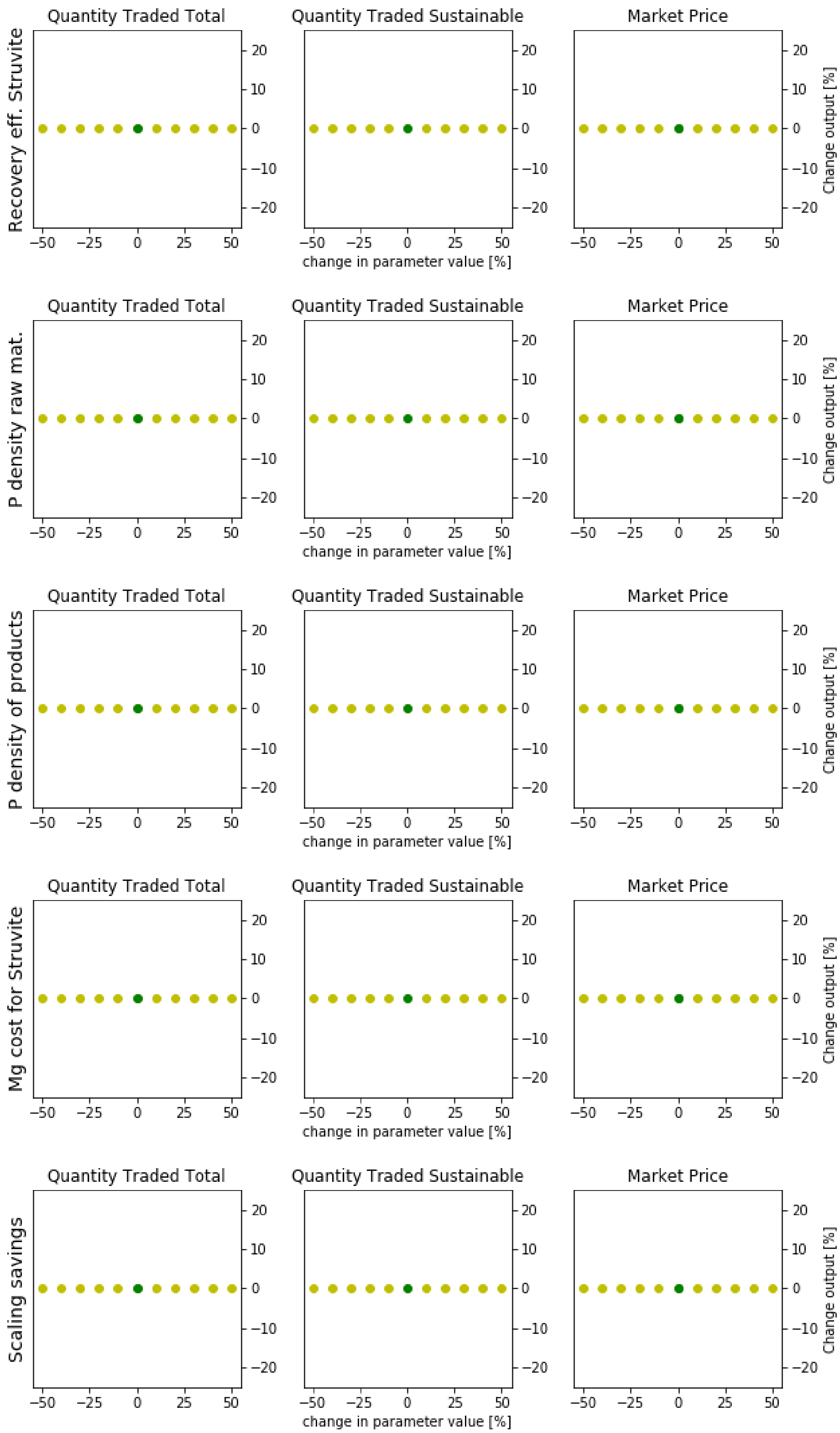


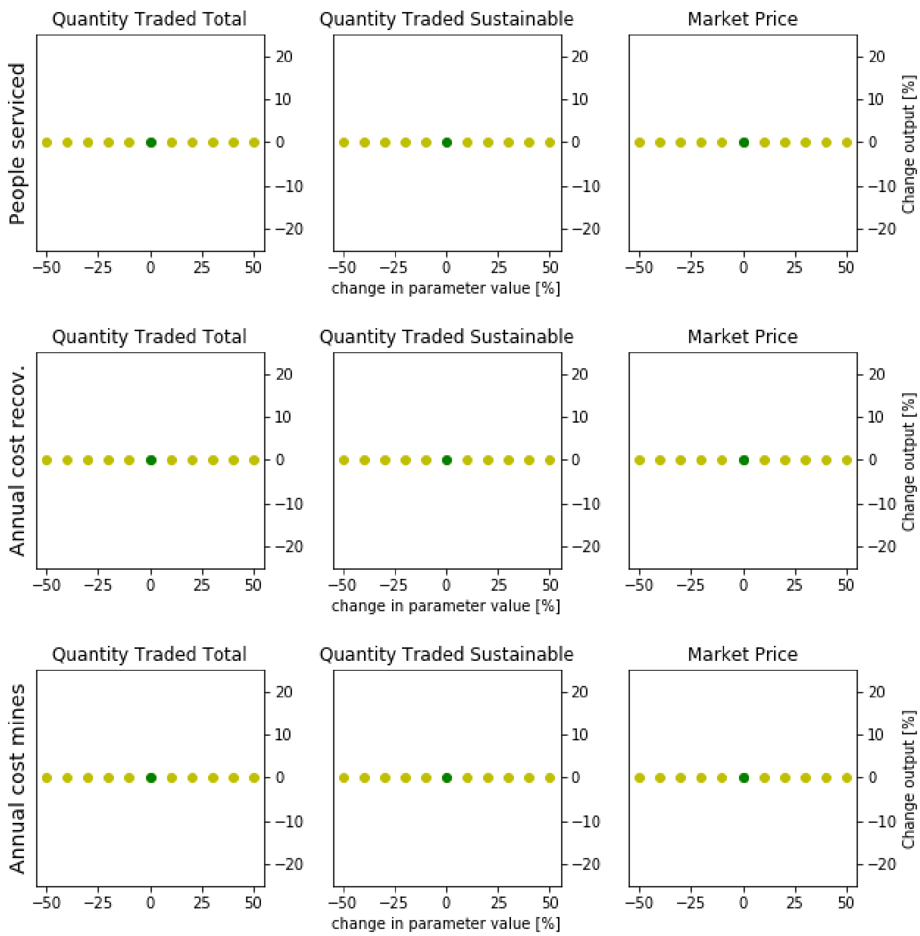
Transport Parameters




Quantity Traded Total
Quantity Traded Sustainable
Market Price
Velocity truck
Velocity ship
Truck labour cost
Fixed cost truck
Fixed cost ship
change in parameter value [%]
Change output [%]

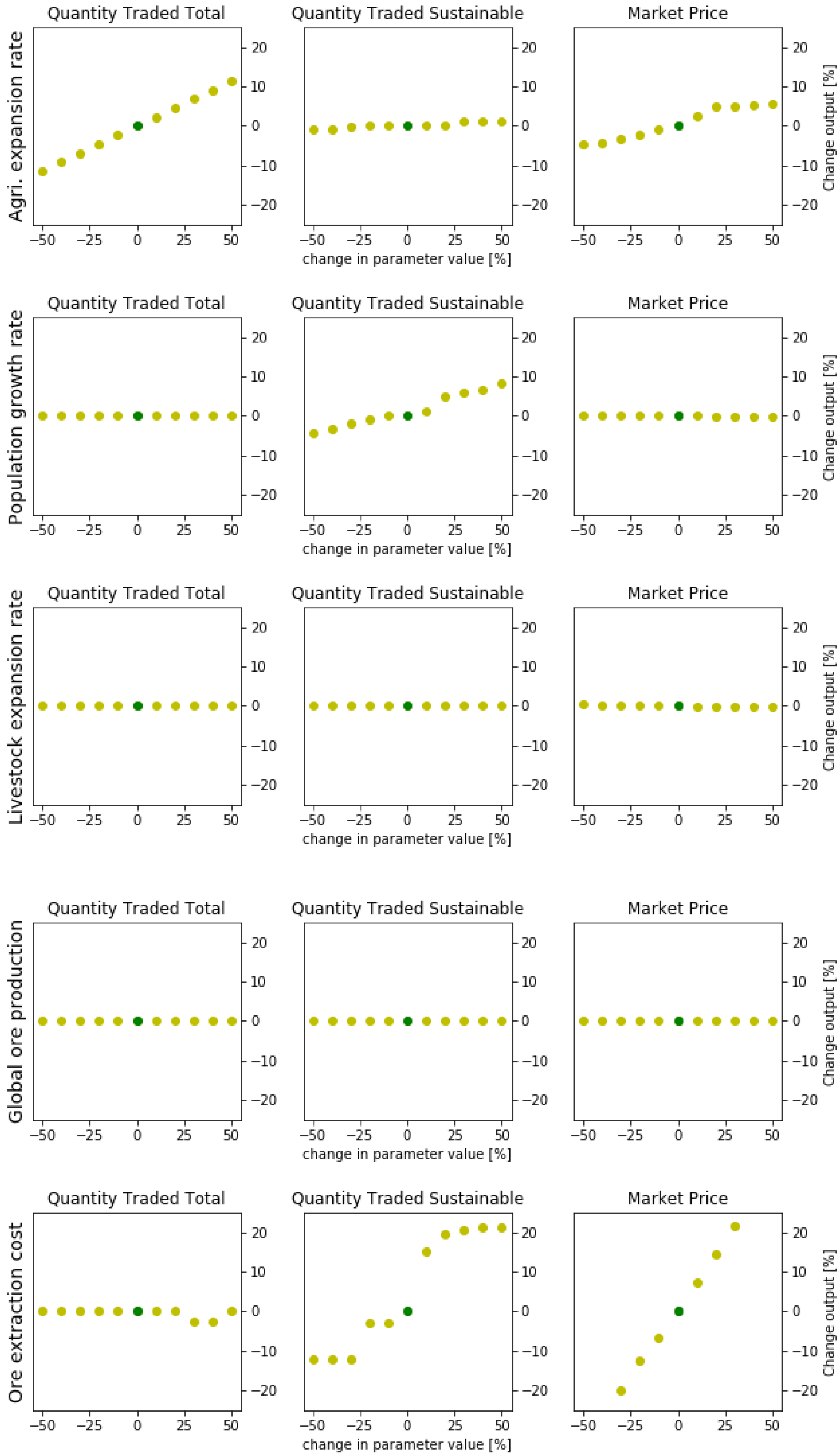
Recovery Parameters





Quantity Traded Total
Quantity Traded Sustainable
Market Price
People serviced
Annual cost recov.
Annual cost mines
Change output [%]
change in parameter value [%]
20
10
0
−10
−20
−50
−25
0
25
50

Market Parameters (yearly input data)



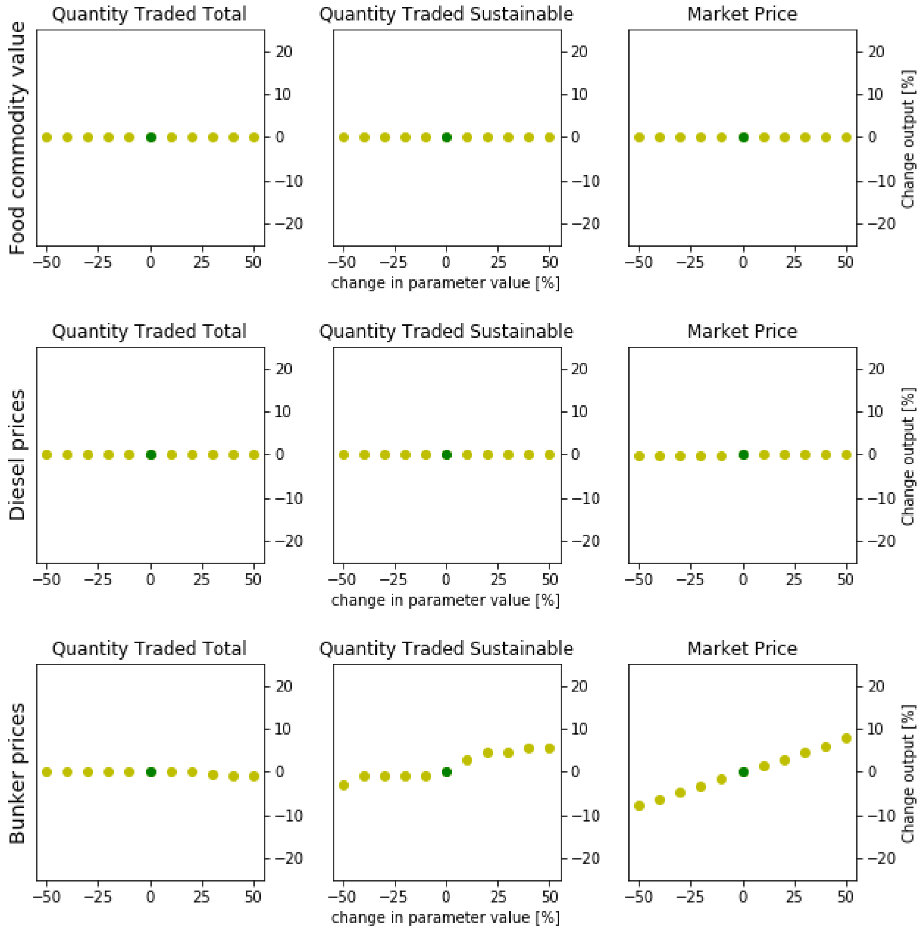


Figure S3. Figures reveal how -50% to +50% change in parameter influences the model determined total quantity of phosphorus traded (1st column), the total quantity of recovered products traded (2nd column), and the optimal market price (3rd column). Green marker shows original parameter value with original output. Yellow marker shows relative change in output (y-axis) vs. relative change in parameter (x-axis).

Supplementary Tables

S1. 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
Bovine (Unsp.)	10		Global	Sheldrick et al., 2003
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
Poultry (Unsp.)	0.19		Global	Sheldrick et al., 2003
Swine (sow)	6.4		NL	CBS, 2014
Swine (Unsp.)	4		Global	Sheldrick et al., 2003
	4.1		US	Barker et al., 2001
	2.1		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.

S2. Crop Phosphorus Requirement Data

Crop	Ky [-]	Water req. [mm/harvest]	Growing Period [days]	P_2O_5 Range [kg/ha]	P_2O_5 Choice [kg/ha]	P [kg/ha]
Maize	1.30	500-800	80-180	36-50	50	22
Wheat	0.55	450-650	120-150	27-60	40	15
Rice[1]	1.00	450-700	90-150	26-50	35	15
Soybean	0.90	450-700	135-150	35	35	15
Sorghum	0.90	450-650	120-130	20-40, 40-60	40	15
Potato	0.90	500-700	105-145	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

S3. Transportation Cost Data

Sea Transport Component Cost				**Land Transport Component Cost**			
Constant		**Value**	**Source**	**Constant**		**Value**	**Source**
E_W	[t d^{-1}]	93.1	(Počuča, 2006)	E_L	[L km^{-1}]	0.53	(Nylund and Erkkilä, 2005)
W_W	[t]	2,777	(Počuča, 2006)	W_L	[t]	60	
$\bar{V}_W$	[km d^{-1}]	924	(Počuča, 2006)	$\bar{V}_L$	[km h^{-1}]	80	-
C_F	[$ d^{-1}]	9,989	(Počuča, 2006)	L_c	[$ h^{-1}]	15	-
				C_d	[$ km^{-1}]	0.5	

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

S4. Yearly variable input data

	Global Phosphate Ore extraction cost (World Bank, 2018a)[2] **[$ t^{-1}]**	**Global Phosphate Ore production** (USGS, 2016)[3] **[kt]**	**Food Price Index** (FAO, 2018a)[4] **[-]**	**Diesel Fuel Price** (U.S. Energy Information Administration, 2018)[5] **[$ gal^{-1}]**	**Bunker Fuel Price** (Institut National de la Statistique et des Etudes Economiques, 2017)[6] **[$ t^{-1}]**
2005	42.00	147,000	118	2.402	248
2006	44.21	142,000	127	2.705	290
2007	70.93	156,000	161	2.885	341
2008	345.59	161,000	201	3.803	522
2009	121.66	166,000	160	2.467	355
2010	123.02	181,000	188	2.992	464
2011	184.90	198,000	230	3.840	642
2012	185.89	217,000	213	3.968	672
2013	148.11	225,000	210	3.922	613
2014	110.22	218,000	202	3.825	546
2015	117.46	241,000	164	2.707	291

Table S4. Model yearly variable input data

[2] http://pubdocs.worldbank.org/en/226371486076391711/CMO-Historical-Data-Annual.xlsx
[3] https://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/
[4] http://www.fao.org/worldfoodsituation/foodpricesindex/en/
[5] https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm
[6] https://www.insee.fr/en/statistiques/serie/001642883

S5. Fixed Parameters

Yearly population growth rate	1.22	[%]	(World Bank, n.d.)
Yearly livestock growth rate	0.8	[%]	(FAO, 2018b)
Yearly agricultural expansion rate	3	[%]	[-]
Struvite recovery efficiency WWTP	0.2	[-]	Derived from (Jaffer et al., 2002)
Phosphorus density urine (for intracity transport)	0.00066	[-]	(Vinnerås, 2001)
Phosphorus density faeces (for intracity transport)	0.00457	[-]	(Vinnerås, 2001)
Phosphorus density rock phosphate	0.08	[-]	18% P_2O_5 rock phosphate
Phosphorus density Struvite	0.14	[-]	-
Phosphorus density compost pellets	0.01	[-]	(Cofie and Nikiema, 2012)
Phosphorus density DAP	0.2	[-]	[-]
Price Magnesium Chloride	250	[$ t^{-1}]	(Seymour, 2009)
Scaling maint. savings per mass P recovered	0.89	[$ kg^{-1}]	(Shu et al., 2006)
Intracitiy collection distance	20	[km]	[-]
People serviced per WWTP	500,000	[p]	(Egle et al., 2016)
Annual costs Struvite precipitation	180,000	[$ a^{-1}]	(Egle et al., 2016)
Annual costs pelletizing facilities	20,000	[$ a^{-1}]	[-]
Pelletizing cost per mass influent	30	[$ t^{-1}]	(Masayuki Hara, 2001)
Annual costs mines (Inv. cost spread over 10 years)	3,100,000	[$ a^{-1}]	(World Bank, 2018b)

Table S5. Model yearly variable input data

S6. Livestock Phosphorus in Excrement

Global P	Year [-]	Cattle [Mt]	Swine [Mt]	Poultry [Mt]	Livestock Total [Mt]
This study	2006	11.22	3.66	2.51	17.39 (8.8)
Bouwman et al., 2013	2000	-	-	-	17
Sheldrick et al., 2003	1996	10.43	3.55	2.74	16.72

Table S6. Comparison of estimates of global phosphorus produced in the form of excrement by different livestock types, for different years. Estimates made following slaughter weight methodology proposed by (Sheldrick et al., 2003). In brackets for this study, shows contribution of major sites (production greater than 0.5 [t km^{-2}] P and greater than 3 [kt] P total

S7. Table of Sensitivity Analysis

Parameter Change	-50%	-40%	-30%	-20%	-10%	+10%	+20%	+30%	+40%	+50%	Sensitivity
	Change in P Market Price with Following Changes in Parameter Value:										
Crop Parameter											
P Req. for optimal yield	6	4	3	2	1	-1	-1	-1	-2	-2	0.39
Optimal yield	-7	13	-2	-1	-1	1	1	2	3	3	0.26
Crop sale value	-7	13	-2	-1	-1	1	1	2	3	3	0.26
Proportion of fertilizer of production cost	-7	13	-2	-1	-1	1	1	2	3	3	0.26
Proportion P-fert. cost of total fert. cost	-7	13	-2	-1	-1	1	1	2	3	3	0.25
Recovery Parameters											
Recovery Efficiency Struvite Precip.	0	0	0	0	0	0	0	0	0	0	0.00
P density of raw wastes	0	0	0	0	0	0	0	0	0	0	0.00
P density of recovered products	0	0	0	0	0	0	0	0	0	0	0.00
Magnesium cost for struvite	0	0	0	0	0	0	0	0	0	0	0.00
Scaling maintenance savings	0	0	0	0	0	0	0	0	0	0	0.00
Intracity waste collection distance	0	0	0	0	0	0	0	0	0	0	0.00
People serviced per recovery installation	0	0	0	0	0	0	0	0	0	0	0.00
Annual fixed cost per recovery installation	0	0	0	0	0	0	0	0	0	0	0.00
Annual cost mines operation	0	0	0	0	0	0	0	0	0	0	0.00
Transport parameters											
Truck fuel efficiency	0	0	0	0	0	0	0	0	0	0	0.00
Ship fuel efficiency	-12	-10	-7	-5	-3	2	5	7	10	12	0.24
Truck maximum carry load	9	6	4	2	1	-1	-1	-2	-3	-3	0.17
Ship maximum carry load	85	33	21	12	5	-5	-8	-11	-14	-16	1.00
Truck velocity	2	2	1	1	0	0	0	-1	-1	-1	0.05
Ship velocity	43	29	18	11	4	-4	-7	-10	-12	-14	0.87
Truck labour cost	-1	-1	-1	-1	0	0	0	1	1	1	0.02
Truck fixed costs	-3	-3	-2	-1	-1	1	1	2	2	3	0.06
Ship fixed cost (incl. labour)	-11	-9	-7	-5	-2	2	4	6	9	11	0.22
Yearly input data											
Ore extraction cost	-21	-17	-13	-9	-4	4	8	13	17	21	0.43
Global ore production	0	0	0	0	0	0	0	0	0	0	0.00

Food commodity price index	0	0	0	0	0	0	0	0	0	0	0.00
Diesel prices	0	0	0	0	0	0	0	0	0	0	0.00
Bunker prices (ship fuel)	-12	-10	-7	-5	-3	2	5	7	10	12	0.24
Population growth rate	0	0	0	0	0	0	0	0	0	0	0.00
Livestock expansion rate	0	0	0	0	0	0	0	0	0	0	0.00
Agricultural expansion rate	0	0	0	0	0	0	0	0	0	0	0.00

Table S7. This table presents the results of a sensitivity analysis. It reveals how sensitive the model price predictions are to changes in parameter values (other parameters kept constant). A single 'sensitivity' value is determined for each parameter. A value of '1' indicates that the model is highly sensitive to that value, where a (up to 50%) change in parameter value may result in an equal or greater percent change in model output. A value of '0' indicates that the model price output is insensitive to (up to 50%) changes in parameter value. The table shows that the model is most sensitive to changes in transport parameters. Remarkably, the model market prices are relatively insensitive to changes in recovery costs. This is likely because of the insignificant share of recovered P on the total P market.

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