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# Citation for the published paper:

Koppelaar R.H.E.M., Weikard H.P., (2013). Assessing phosphate rock depletion and phosphorus recycling options. *Global Environmental Change*. 23(6). pp. 1454-1466. doi:10.1016/j.gloenvcha.2013.09.002

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# Assessing phosphate rock depletion and phosphorus recycling options

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# Abstract

We analyse global elemental phosphorus flows in 2009 for 1) mining to products, 2) animal and human manure flows, 3) crop harvests and animal production, 4) food production, 5) soil erosion, 6) and crop uptake. Informed by the flow assessment the potential and cost of phosphorus usage reduction and recycling measures are quantified, and fed into a constructed phosphorus supply-demand model with reserve assessment to assess the impact of these measures on phosphate rock resource availability. According to our results in 2009 globally 21.4 Mt elemental phosphorus from rock phosphate was consumed in products of which 17.6 Mt used as fertilizers, fully able to cover erosion losses and outputs in agriculture in aggregate, but insufficient from the perspective of bio-available phosphorus in soils. We find substantial scope for phosphorus use reduction, at potentially 6.9 Mt phosphorus, or 32% of 2009 phosphate rock supply. Another 6.1 Mt, or 28% can technologically be recycled from waterways and wastewater, but at a cost substantially above any foreseeable phosphate rock fertilizer price. The model results suggests phosphate rock reserves are sufficient to meet demand into the 22nd century, and can be extended well into the 23rd century with assessed use reduction and recycling measures.

#### 1. Introduction

#### **1.1 The importance of phosphorus**

Phosphorus (P) is essential for cellular activity making it non-substitutable for life. Worldwide approximately 17.6 Mt of phosphorus was extracted in 2009 from phosphate rock mining operations for conversion and application as fertilizer, and 3.8 Mt for other purposes. Without this supply humanity cannot sustain agricultural productivity and present food production output. Obviously, phosphorus cannot be extracted out of finite mineral deposits forever to compensate for use losses.

#### 1.2 Phosphate rock availability: The recent discussion

Substantial interest in phosphorus availability was sparked by Cordell et al. (2009), who in an updated study using enhanced phosphate rock reserve data ascertained a peak around 2070 (Cordell et al. 2011). Others demonstrated sufficient availability to sustain production beyond the 21<sup>st</sup> century (Cooper et al. 2011; Van Vuuren et al. 2010), or a maximum occurring late 21<sup>st</sup> century (Sverdrup and Ragnarsdottir 2011). The variability in outcomes, detailed in table 1, is caused firstly by resource-reserve assumptions. Rigorous rock sampling of deposits is necessary to inform reserve assessments, but no financial incentives exist to initiate examinations across hundreds of kilometers when mine exploitation is not on the horizon. Available data was summarized by Kauwenbergh (2010), yielding a known resources base of 290 Gt phosphate rock, of which 60 Gt deemed currently extractable. The results were incorporated in the mineral data reference work, the USGS Minerals Yearbook, which upgraded reserves from 16 to 65 Gt phosphate rock in 2011, primarily assigned to Morocco (Jasinski 2010; Jasinski 2011). The second reason is the treatment of supply and demand dynamics. Reserve estimates differ due to in- or exclusion of price effects on reserve availability, since lower quality deposits become feasible to exploit with price increases.

Author(s)		Assu	imed resource	es and reserv	/es*	Datasource	Conclusions
(year)	Approach		Phosphate	P <sub>2</sub> O <sub>5</sub>	Р		
	rippiodoli		rock (Gt)	(Gt)	(Gt)		
			none	none	none		
Van Vuuren Fir et al. (2010)	Finite resource	Reserves	44.1 - 105.6	11.6 - 27.8	5.4 - 12.9	Range of	Production increases beyond 2100 with
	feedback	Resources	58.5 - 318.1	15.4 - 83.7	7.1 - 38.8	sources	rising prices towards 100-200 USD ton <sup>-1</sup>
Cooper et al. (2011) Finite res stock / no feedbac	Finite reserve	Reserves	65	17.1	7.9	Jasinski	Sufficient reserves exist for the 21 <sup>st</sup>
	stock / no price feedback	Resources	none	none	none	(2011)	century but production increasingly dominated by Morocco
Sverdrup and		Reserves	43	11.3	5.2	Unknown, data	Production peaks mid- 21 <sup>st</sup> century, declines slowly by 60% to 24th
Ragnarsdott ir (2011)	causing peak behaviour	Resources	50	13.2	6.1	published reference	century, and remains at a plateau until 33 <sup>rdf</sup> century
Cordell et	Finite reserve	Reserves	60	15.8	7.3	Kauwenbergh	A probable peak
al. (2011)	effects	Resources	none	none	none	(2010)	with a 2070 mean

Table 1 – Summary of recent phosphorus availability studies

\*In case one value was published conversion factors were applied to obtain three categories.

#### 1.3 The aim of this paper

The conducted phosphate rock availability assessments exclude use reduction and recycling measures. Only van Vuuren et al. (2010) included management measures, but on a scenario basis without analysing disaggregate potentials and costs. The objective of this study is to fill this gap. We estimate the potential of use reduction and recycling measures and their impact on phosphate rock availability by (i) expanding previous global flow assessments in section 2, (ii) using quantified flows to analyse management measures in section 3, (iii) providing a partial-equilibrium model described in section 4, to gain insights in phosphate rock reserve longevity with and without management measures. Main results are presented and discussed in section 5. Section 6 concludes. In the paper quantities are published as tonnes elemental phosphorus unless mentioned otherwise.

#### **1.4 Analytical framework**

The paper employs three methodologies to present a global picture of phosphorus availability and recycling. We start with a global phosphorus *inputs-outputs flow estimation* across sectors quantified using statistical aggregate flow data, the phosphorus flow share, and estimated losses. Subsequently, a *reduction and recycling flow and cost quantification* is applied to flows generated by the inputs-outputs flow estimation. For this purpose an assumed reduction/recycling percentage is estimated for input-output flows based on a literature assessment, complemented with cost estimations for technologies. After this, *a partial-equilibrium model* is presented to estimate the longevity of the reserve base with and without recycling and use reduction using four scenarios. Data on prices, demand, reserves, mining outputs from the flow analysis, and quantity and costs of use reduction/recycling approaches are used to parameterize the model. Phosphate rock resources and reserves data was obtained from the literature. Figure 1 gives an overview of our analytical framework.



Figure 1 – Schematic description of relationship between methodologies. Source: this study

## 2. Global flow analysis

#### 2.1 Methodology

We build upon the methodologies in Smil (2000), Liu et al. (2008), and Liu et al. (2004) to estimate 2009 global phosphorus flows. In total eight areas with interrelations are analysed, as shown in figure 2, including phosphate rock production & processing into phosphoric acid, crop harvests, food production & consumption, domestic animal flows, human food input and excreta, soil erosion, and phosphorus bio-availability. Some aspects are ignored including airborne soil erosion, internal marine ecosystem flows, and soil-biota interactions.



Figure 2 - Global phosphorus flow components schematic. Source: this study

Similar to Liu et al. (2004) mathematical equations and variables in the model can be classified as (i) *exogenously fixed variables*, which represent absolute values from statistical sources here converted into elemental phosphorus, (ii) *dependent equations*, that describe a flow as a portion of another flow using a parameter value, typically a mean value was taken from literature sources, but if no information was available an assumption was introduced, and (iii) *balancing equations* based on the mass conservation law stating that flow inputs need to be equal to outputs.

#### 2.1 Flow model results

The mathematical equations, parameters, and flow quantities, are provided in table 2 below together with the estimation approach. In tables 8-13, available in Appendix B in the supplementary materials, details have been added for *dependent equations* operating at a disaggregate level. Results are discussed and visually depicted in section 5.1.

Flow n.	P flow description	2009 Value* (Mt P)	Input data Reference / Approach	Equation	Coe	fficient description & 2009 value
X <sub>1</sub>	Phosphate rock ore extraction	22.8	Literature data	$X_1 = 162 * 10^6 *$	K <sub>1</sub> = 0.32	K <sub>1</sub> , Conversion from metric tons phosphate rock to P <sub>2</sub> O₅ elemental P
			(0565 2012)	$\mathbf{r}_1$ $\mathbf{r}_2$	K <sub>2</sub> = 0.44	$K_2$ , Conversion from $P_2O_5$ to elemental P
<b>X</b> <sub>2</sub>	Phosphate rock ore extraction pre-beneficiation	30.4	Literature mean (Fantell et al. 1988) Abouzeid (2008)	$X_2 = X_1 / (1 - K_3)$	K <sub>3</sub> = 0.25	K <sub>3</sub> , Beneficiation loss
$X_3$	Phosphate losses in beneficiation	7.6	Mass balance	$X_3 = X_2 - X_1$		
$X_4$	Phosphoric acid processing & handling loss	1.4	Literature minimum (Fantell et al. 1988)	$X_4 = X_1 * K_4$	K <sub>4</sub> = 0.06	K <sub>4</sub> , Phosphorus loss during phosphoric acid production
X <sub>5</sub>	Phosphoric acid production	21.4	Mass balance	$X_5 = X_1 - X_4$		
$X_6$	Phosphorus in produced fertilizers	17.7	Literature data (FAO 2011e)	$X_6 = 40 * 10^6 * K_2$		
×.	Phosphorus in produced				K <sub>5</sub> = 0.09	$K_5$ , industrial & food phosphoric acid use share
X <sub>7</sub>	detergents	1.1		$X_7 = X_5 * K_5 * K_6$	K <sub>6</sub> = 0.59	$K_6$ , share of $K_5$ used in detergents & cleaners
$X_8$	Food products additives phosphorus	0.2	Literature data (Potashcorp 2009)	$X_8 = X_5 * K_5 * K_7$	K <sub>7</sub> = 0.11	K <sub>7</sub> , share of K₅ used in food & beverages
X <sub>9</sub>	Livestock feed additives phosphorus	1.3		X <sub>9</sub> = X <sub>5</sub> * K <sub>8</sub>	K <sub>8</sub> = 0.06	K <sub>8</sub> , share of phosphoric acid converted to feed additives
X <sub>10</sub>	Phosphorus in produced pesticides	0.1		$X_{10} = X_5 * K_5 * K_9$	K <sub>9</sub> = 0.07	K <sub>8</sub> , share of K₅ used in pesticides
<b>X</b> <sub>11</sub>	Other industrial use production	1.1	Marahalawaa	$\begin{array}{c} X_{11} = X_5 - X_{10} - X_9 \\ - X_8 - X_7 - X_6 \end{array}$		
X <sub>12</sub>	Livestock feed additives consumed by domestic animals	1.2	Mass balance	X <sub>12</sub> = X <sub>9</sub> - X <sub>11</sub>		
X <sub>13</sub>	Livestock feed additives handling losses ending in landfills	0.1	Loss assumption	$X_{13} = X_7 * K_{10}$	K <sub>10</sub> = 0.06	$K_{10}$ , Handling losses of livestock feed additives
X <sub>14</sub>	Agricultural fertilizer application	16.7	Literature data (IFA 2012)	X <sub>14</sub> = 38.0 * K <sub>2</sub>		
X <sub>15</sub>	Agricultural pesticide application	0.1	Mass Balance	$X_{15} = X_{10}$		
X <sub>16</sub>	Animal manure production by domestic animals	28.3 (12.3)	Calculation from literature data (table 10 supplements)	X <sub>16</sub> = 28.3		
X <sub>17</sub>	Animal manure application to agriculture	28.3 (12.3)		X <sub>17</sub> = X <sub>16</sub>		
X <sub>18</sub>	Animal grazing	24.9	Mass balance	$\begin{array}{c} X_{18} = X_{16} + X_{25} - X_{19} \\ - X_{24} + X_{12} \end{array}$		
X <sub>19</sub>	Crop residue consumption by domestic animals	1.2	Literature data (Liu et al. 2008)	$X_{19} = X_{22} * K_{12}$	K <sub>12</sub> = 0.25	K₅, fraction of crop loss & residue consumed by
X <sub>20</sub>	Crop loss & residue degradation on fields	3.8 (2.3)	Mass balance	X <sub>20</sub> = X <sub>22</sub> - X <sub>19</sub>		
<b>X</b> <sub>21</sub>	Phosphorus inputs from soil into crops	12.5	Calculation from literature data (table 8 supplements)	X <sub>21</sub> = 12.5		

#### Table 2 – Data and equations of the phosphorus mass balance model

X <sub>22</sub>	Crop residue & field losses of crops	5	Calculation from literature data (tables 8 & 9	$X_{22} = 4.5 + 0.5$		
X <sub>23</sub>	Harvested crops by humans	7.5	Mass balance	X <sub>23</sub> = X <sub>21</sub> - X <sub>22</sub>		
X <sub>24</sub>	Harvested crops fed to domestic animals as animal feed	2.3	Calculation from	X <sub>24</sub> = 2.3		
X <sub>25</sub>	Animal meat and products (eggs, milk) converted into human food products	1.3	literature data (FAO 2011c)	X <sub>25</sub> = 1.3		
X <sub>26</sub>	Harvested crops used in human food consumption	4.3	Mass balance	$X_{26} = \begin{array}{c} X_{23} - X_{24} \\ - X_{36} - X_{27} \end{array}$		
X <sub>27</sub>	Loss of harvested crops in postharvest handling & storage	0.6	Calculation from literature data (Gustavsson et al.	X <sub>27</sub> = 0.6		
X <sub>28</sub>	Food wastes applied to agricultural fields	0.8 (0.5)	Conversion assumption	$X_{28} = K_{13} *$ (X <sub>29</sub> + X <sub>27</sub> + X <sub>30</sub> )	K <sub>13</sub> = 0.3	K <sub>13</sub> , fraction of food waste converted into compost
X <sub>29</sub>	Loss of food products in processing, packaging, supermarket retail	0.95	Calculation from literature data (table 9	X <sub>29</sub> = 1		
X <sub>30</sub>	Food wastes during human consumer handling	1.1	supplements)	X <sub>30</sub> = 1.1		
X <sub>31</sub>	Phosphorus in food consumed by humans	5.25		$\begin{array}{rl} X_{31} = & X_{26} + X_{39} + X_8 \\ & + & X_{25} - & X_{29} \end{array}$		
X <sub>32</sub>	Phosphorus loading into human excreta	4.2	Mass balance	$X_{32} = X_{31} - X_{30}$		
X <sub>33</sub>	Food waste collected and dumped in landfills	1.9		$X_{33} = (X_{30} + X_{29} + X_{27}) - X_{28}$		
X <sub>34</sub>	Human excreta applied directly in agriculture	2.1 (0.7)	Agricultural application assumption	X <sub>34</sub> = X <sub>32</sub> * K <sub>15</sub>	K <sub>15</sub> = 0.50	K <sub>15</sub> , fraction of human excrements applied in agriculture
X <sub>35</sub>	Human excreta ending up in marine ecosystems through wastewater systems	2.1 (0.7)	Ecosystem flow assumption	X <sub>35</sub> = X <sub>34</sub> * K <sub>16</sub>	K <sub>16</sub> = 0.50	K <sub>15</sub> , fraction of human excrements ending up in marine ecosystems
X <sub>36</sub>	Harvested crops converted into non-food commodities	0.3	Calculation from literature data (FAO 2011b)	X <sub>36</sub> = 0.3		
X <sub>37</sub>	Non-food commodities consumption flow into landfills	0.3	Mass balance	X <sub>37</sub> = X <sub>36</sub>		
X <sub>38</sub>	Soil erosion from non-agricultural ecosystems into the sea	12.0 (6.0)	Calculation from literature data (table 11 supplements)	X <sub>38</sub> = 12.0		
X <sub>39</sub>	Fish catch phosphorus flow	0.4	Calculation from literature data (FAO 2011a)	X <sub>39</sub> = 0.4		
X <sub>40</sub>	Soil erosion from agricultural ecosystems into the sea	13.7 (6.8)	Calculation from literature data (table	X <sub>40</sub> = 13.7		
X <sub>41</sub>	Phosphorus content in other industrial materials ending up in landfills	1.1	TT SUDDIEMENTS)	X <sub>41</sub> = X <sub>11</sub>		
X <sub>42</sub>	Fertilizer handling losses ending up in landfills	0.8	Mass balance	$X_{42} = X_4 - X_{10}$		
X <sub>43</sub>	Loading from detergents in non- agricultural ecosystems	1.1		$X_{43} = X_7$		

\* Values between brackets refer to the inorganic fraction of the phosphorus flow, for details see table 8.

#### 3. Recycling and use reduction measures

The potential of recycling and use reduction measures was informed by the flow assessment quantities (section 2.1). The appropriate flow was multiplied for each measure by a percentage parameter indicating the flow portion that could be recycled or reduced, with a static cost level for the measure assumed based on literature data. A flow and cost measures results summary can be found in table 11, section 5.2, with details found below:

- Colas phosphorus substitution, at 0.1 Mt as a food & beverage content fraction from flow X<sub>8</sub> in table 2, based on substituting phosphoric acid used for acidulation in colas, assuming 527 billion liters production of colas in 2009 with 17 mg phosphorus per 100 grams.
- 2) Detergent reduction, at 1.1 Mt based on flow X<sub>7</sub> in table 2, by substitution of sodium tripolyphosphate in detergents. Substitution for laundry detergents with zeolites already has been implemented in the US and EU (Glennie et al. 2002; Litke 1999). Substitution for dishwasher detergents at present takes place in several US states, its diffusion is constrained by lower performance of substitutes (European Commission 2010; Walsh 2010).
- 3) Food wastage reduction, at 0.51 Mt from flows X<sub>29</sub> and X<sub>30</sub> in table 2, assuming 20%-35% reduction potential over existing food chain losses. The avoidable share of UK food chain loss through behavioural change and food production chain adjustments was estimated at 64% (Lee and Willis 2010), demonstrating theoretical feasibility for significant reduction. Yet, substantial efforts have not been forthcoming (Parfitt et al. 2010).
- 4) Food waste recycling, at 1.44 Mt from flows X<sub>28</sub>, X<sub>33</sub>, and X<sub>37</sub> in table 2, using anaerobic digestion, separation into liquid and solid fractions, and drying (Fuchs et al. 2010; Vlaco 2010). Cost of the drying route net of biogas revenues and assuming no raw material cost is 7030 euro ton<sup>-1</sup> concentrate (Westeinde 2009; Gebrezgabher et al. 2010). We assumed 80% food and non-food commodities waste processed using this route after food waste reduction.
- 5) Urban wastewater treatment, at 2.1-2.8 Mt recovery based on flows X<sub>35</sub> and X<sub>43</sub> in table 2, varying by in- or exclusion of detergent use reduction. Cost of wastewater plants operating since the 1990s ranges between 8,000-15,000 USD ton<sup>-1</sup> of phosphorus (inflation corrected 2010 USD), 30-40 times equivalent phosphate rock product cost (Lundin et al. 2004, Geraats et al. 2007, Piekema 2004). Substantial cost reduction has been demonstrated by

a new 80%+ efficient treatment technology to produce struvite from wastewater, a phosphate rock fertilizer equivalent compound, estimated at 5300-8200 USD ton<sup>-1</sup> phosphorus (Seymour 2009), of which the mean 6750 USD ton<sup>-1</sup> was taken here as treatment cost. The facility also recovers 15%+ nitrogen from the treatment stream signalling that joint recovery of P, N, and K could improve recovery economics.

- 6) Bio-fertilizer application, at 1.67 Mt reduction assuming 10% reduction of phosphorus fertilizer application as per flow X<sub>14</sub> in table 2, by application of phosphorus solubilizing bio-fertilizing micro-organisms. Theoretical potential was demonstrated at up to 50% fertilizer reduction without crop yield reduction under controlled conditions (Jilan et al. 2007; Zabihi et al. 2011), but translation to a field situation has been unsuccessful, possibly due to plant-soil interaction knowledge gaps, differences between plant and soil types, and incorrect micro-organism strain selection (Uribe et al. 2010).
- 7) No-till agricultural expansion, at 3.5 Mt reduction half from farms below and half above 200 hectares, due to reduced erosion of soil, related to flow X<sub>40</sub> in table 2. No-till erosion was estimated by Montgomery (2007) at a mean 0.124 mm/year (1.32 tonnes of soil ha<sup>-1</sup> year<sup>-1</sup>) from 47 studies, 30x lower than tillage agriculture. No-till commerciality primarily depends on herbicide application cost versus higher tillage mechanization expense, aided in recent years by lower herbicide cost and rising fuel prices (Epplin 2008; Sánchez-Girón et al. 2007; Langemeier 2010). We assumed accessibility only in middle to high income countries with Global National Income above 4000 USD capita<sup>-1</sup>, and half of croplands suitable for no-till, given farm size and cost constraints (Lal 2007). Furthermore, no-till farming was assumed to impose additional costs of 1030 USD ton<sup>-1</sup> phosphorus erosion on farms below 200 hectares, around 60% of global cropland (Epplin 2008; FAO 2010).
- 8) Phosphorus wetland absorption, at 2.5 Mt reduction assuming a 25% recovery from agricultural erosion from flow X<sub>40</sub> in table 2. Kadlec (2006) analysed 283 wetlands in 10 countries, up to 1800 hectares, with average 55% phosphorus water removal efficiency. Capital costs decrease substantially with wetland size, and average costs for 10+ hectare wetlands is 50 USD ha<sup>-1</sup>. To calculate full costs it was assumed that biomass is transported, processed, incinerated in power plants, electricity is sold, and phosphorus retrieved from fly ash at 6% content (Grosshans 2011; Tan and Lagerkvist 2011). Calculations, detailed in table 3, yielded a wetland recycling costs net of electricity of 7280 USD ton<sup>-1</sup> phosphorus.

Dessess ster		Value	Courses
Process step	Unit	value	Source
Total biomass production	DM tonnes hectare <sup>-1</sup>	12.28	Jakubowski et al. (2010)
%P	Per unit DM	0.3%	Jakubowski et al. (2010)
Wetland capital cost	USD ton <sup>-1</sup> hectare <sup>-1</sup>	50	Kadlec (2006)
Harvesting capital and operational cost*	USD ton <sup>-1</sup> DM	25.4	Calculated using Bryant (1972)
Transport cost**	USD ton <sup>-1</sup>	9.8	Calculated using Bryant (1972)
Pellets production***	ton ton <sup>-1</sup> DM	0.8	This study
Pelletizing capital cost	USD ton <sup>-1</sup>	5.6	Mani et al. (2006)
Pelletizing operational cost	USD ton <sup>-1</sup>	25.2	Mani et al. (2006)
Energy content pellets	MJ kg⁻¹	18	Austin (2011)
Electricity production cost****	USD MWh <sup>-1</sup>	157	IEA (2007), this study
Electricity produced****	kWh ton <sup>-1</sup> pellets	1500	This study
Electricity sale income	USD MWh <sup>-1</sup>	100	This study
Biomass ash phosphorus processing cost*****	USD ton <sup>-1</sup>	7280	Seymour (2009), this study

Table 3 – calculation of biomass harvesting cost from wetlands in 2010 USD

\* Average 10y capital cost at 10% interest rate, 80.000 USD harvester cost, 0.5 hectare hour<sup>-1</sup> efficiency, and 528 hours year<sup>-1</sup>. \*\*Inflation corrected including 500 miles transport distance and associated labour cost.

\*\*\*Including 20% pelletizing plant loss.

\*\*\*\*30% biomass power plant efficiency, 85% load factor, 10% interest rate.

\*\*\*\*\*Assuming 6% biomass ash phosphorus content.

#### 4. Partial Equilibrium model

#### 4.1 Model description

The model is built from a phosphorus supply-demand market equilibrium perspective based on a global profit maximization problem. We ignore distributive aspects as considered in Weikard and Seyhan (2009) between poor and rich countries, as well as possible rents generated from sales of phosphate rock mining companies to fertilizer producers. Phosphate rock holding countries *j* operate as competitive fertilizer producers based on profit, production, and cost functions specified for Diammonium Phosphate fertilizer (DAP), a global phosphorus demand calculation, and solving for supply-demand. Production capacity constrains supply for each country, and phosphate rock substitution is enabled by introducing recycling and use reduction.

The model seeks to optimize economic profit  $\pi$  with time index *t*, based on revenue *R*, as a function of market price p multiplied by phosphorus fertilizer equivalent production *y* per country *j*, minus production cost *C* that are a function of production volume and input prices *w*.

(1) 
$$Max \sum_{i=1}^{J} \pi_{i,t} = R_{i,t}(p, y) - C_{i,t}(y, w)$$

(2) 
$$R_{j,t}(p,y) = p_t y_{j,t}$$

Optimal phosphorus production in each period t is found by setting marginal revenue equal to marginal production cost. Phosphorus demand is calculated from global food requirements.

(3) 
$$D_t(E, N, p) = a \theta E_t N_t p_t^{\sigma}, \quad t \ge 0, \quad \sigma < 0$$

Where *D* is phosphorus demand in tons of 46% phosphorus fertilizer equivalent, *N* population size, *E* is food requirement in kcal capita<sup>-1</sup> year<sup>-1</sup>,  $\theta$  is the fertilizer and non-fertilizer phosphorus ratio, *p* phosphorus fertilizer price in USD,  $\sigma$  a price elasticity parameter, and *a* a parameter to convert kcal food demand into phosphorus fertilizer equivalent tonnage. We introduce a production function to calculate *y*, using a Leontief form with three inputs.

(4) 
$$y_{j,t}(G, F, K) = min(\zeta_j G_{j,t}, \eta_j F_{j,t}, \vartheta K_{j,t}), \quad y_{j,t} \le M_{j,t}$$

Where *G* is phosphate rock mine output in tonnes, *F* tonnes of sulfuric acid for phosphoric acid production, and *K* tonnes of ammonia to produce ammonium-phosphorus fertilizers. Inputs are multiplied by ratio parameters expressing usage relative to output. Production *y* has to be equal or lower than production capacity *M* (equation 9). Since input-outputs have a fixed ratio the cost equation becomes linear with unit costs  $w_k$  of phosphate rock  $w_1$ , sulfuric acid  $w_2$ , ammonia  $w_3$ , and  $w_4$  for other inputs x:

(5) 
$$C_{j,k,t}(w, y) = w_{j,1}G_{j,t}(y) + w_{j,2}F_{j,t}(y) + w_{j,3}K_{j,t}(y) + w_{j,4}x_{j,t}(y), \ w_k \ge 0$$

Costs of phosphate rock extraction plausibly increase over time because of contamination, higher extraction site overburden, lower ore grades, and greater transport distances. The aggregate effect is modelled as a linear cost increase v from cumulative production increases  $G_{cum}$  using a baseline cost  $\iota$  and a maximum cost  $\varpi$ . Prices for ammonia, sulfuric acid, and other inputs are assumed constant. By insertion of (6) into (5) we obtain the final cost equation (7).

(6) 
$$w_{j,t}(G_{cum}) = \iota_j + \nu_j G_{cum,t}, \qquad \iota_j + \nu_j G_{cum,t} \le \varpi$$
  
(7)  $C_{j,k,t}(w, y) = (\iota_j + \nu_j G_{cum,t}) G_{j,t}(y) + w_{j,2} F_{j,t}(y) + w_{j,3} K_{j,t}(y) + w_{j,4} x_{j,t}(y), \quad w_k \ge 0$ 

To simulate deposit reserve limitations we introduce a function for mine capacity H (in tonnes) with mine index *I*. The summation of *H* results in production capacity *M* in each country *j*.

(8) 
$$H_{j,l}(V,t,y,Q) = V_{j,l}(1 - t^{-\delta} - \gamma^{-1 + \sum_{m=1}^{t} y_{j,l,m} / Q_{j,l}}), \text{ if } I_{j,l} > 0$$

(9)  $M_j(H) = \sum_{n=1}^l H_{j,n}$ 

Where *V* is maximum production capacity for each deposit *k*. To introduce capacity ramp up an inverse time function  $t^{-\delta}$  alters *V* with a parameter  $\delta$  defining time to reach maximum capacity. Moreover, processing capacity drops to zero with depleted reserves, defined by summing cumulative production *y* over time *t*, divided by the total phosphate rock reserve *Q* of deposit *k*, adjusted for by a parameter  $\gamma$ . Processing capacity *H* is initialized from initial capacity  $V_{j,1}$  per country *j* set by maximum production in the five years before *t*=0. The parameter  $\delta$  was set to 3 years, and production decline to 4 years by using 10000 for  $\gamma$ .

To start production of a new deposit investment *I* must be positive. The fertilizer market price above or equal to a country's fertilizer production cost  $p_t \ge C_{j,t}$ , sufficient reserves available to warrant *T* production years including present capacity  $Q_{j,t} \ge \sum_{m=t}^{T} M_{j,m}$ , future anticipated demand in the next *u* years within the interval  $t \le u \le T$  higher than global current production capacity  $D_u > \sum_{j=1}^{J} M_{j,t}$ , thereby assuming forward looking behavior. The size of new additional processing capacity *H* is set equal to anticipated demand growth *D* in the next *u* years plus twenty percent operating margin, inferred from industry capacity margins (Newton 2010). Finally, investment takes place first in countries with the subsequent lowest production costs. To enable reduction and recycling a function supplying substitutes *O* for phosphate rock is introduced:

(10)  $O_t(\xi, z) = \xi + \tau z_t^{\varphi}, \quad \xi \leq L, \quad O_t \leq S$ 

The use reduction supply  $\xi$  is assumed cost neutral. Recycling measures  $\tau$  are introduced when their cost *z* in USD ton<sup>-1</sup> equals the phosphorus fertilizer market price, weighed by a factor  $\varphi$  to approximate continuous as opposed to discrete availability. Higher prices thus yield increased substitution set to a limit *S* for all available measures, and a limit *L* for use reduction. Substitution is affected by a central planner reflecting a global resource agreement between

countries. The planner in every period attempts to secure remaining phosphate rock reserves Q at *X* future production years by introducing reduction and recycling substitutes.

(11) 
$$D_t(y,0) = \sum_{r=1}^J y_{r,t} + O_t, \quad \sum_{s=1}^J ((Q_{j,0} - \sum_{u=0}^t y_{j,u})/y_{j,t}) \ge X$$

#### 4.2 Model resources & reserves data input

The available global phosphate resource assessments bundle studies dating back one or more decades. During that time companies used their own reporting standard, usually without proper documentation, as opposed to today's standardized reporting practice (JORC 2012). Therefore, a loose categorization not reflecting standardized reserve reporting is applied:

- Known reserves, assessed as economic to produce by respective study authors;
- Potential reserves, based on technologically producible resources, despite economic conditions not warranting extraction at the time of study;
- Demonstrated resources, established with some certainty from appraisal drilling. In case no data was available inferred resource estimates from geological mapping was taken.

The categories were populated with data from Kauwenbergh (2010), complemented with additional sources to distinguish between categories above (Table 7, Appendix A, supplementary materials).

#### 4.3 Model price elasticity

To parameterize demand equation (3) phosphorus fertilizer price elasticity was estimated using 1962-2009 fertilizer consumption (IFA 2012) and inflation adjusted DAP fertilizer prices (World Bank 2011). In the dataset 22 years of price increases occur, of which 6 with negative price elasticity, and 16 where demand rises despite 20%+ price increases. Low demand elasticity is due to the essentiality of food and the low fertilizer production cost share. Therefore years were selected where the fertilizer price rose 50%+ yielding a -0.076 price elasticity  $\sigma$  value.

## 4.4 Fertilizer consumption trends

Historic phosphate fertilizer consumption and population trends were inspected from 1961-2009 to assert the validity of proposed demand equation (3), which assumes fertilizer demand to be dependent on population growth and food consumption. Trends were inspected in absolute levels, as average hectare<sup>-1</sup> year<sup>-1</sup>, and capita<sup>-1</sup> year<sup>-1</sup>, using population data (United Nations 2012), agricultural area (FAO 2011d), and phosphorus fertilizer use (FAO 2011e). Absolute

phosphorus fertilizer consumption in the EU-15 is declining since the 1970s, fairly stable in the USA since the 1980s, increasing for both India and China since the 1960s, and Brazil since late 1990s. The former Soviet Union (FSU) demonstrates increasing consumption from the 1960s to 1980s with a sharp drop after its breakup and only a minor recovery since. The slow recovery is plausibly attributable to over-application, since crop yields after the breakup declined less than fertilizer consumption, and even increased for grains (Liefert 1995). Also EU-15 decline is plausibly explained by initial over-application with 1970s average consumption of 16.6 kg P hectare<sup>-1</sup>, down to 5.6 kg P hectare<sup>-1</sup> in 2009 (Fertilizers Europe 2010). In comparison, 1970s US application levels averaged 4.8 kg P hectare<sup>-1</sup> versus 3.6 kg P hectare<sup>-1</sup> today, application in China and India grew from practically nil to respectively 12.8 and 17.6 kg P hectare<sup>-1</sup> in 2009, and Brazil consumed around 2.8 kg P hectare in the 1980s and 1990s <sup>-1</sup>, growing to 5.1 kg P hectare<sup>-1</sup> in the 2000s.

At a global scale an analysis in- and excluding FSU was made. The global series for absolute phosphorus fertilizer consumption including FSU shows a significant decline from 1988 to 1993 with absolute recovery taking until 2004, consumption in kg capita<sup>-1</sup> still has not recovered and consumption in kg hectare<sup>-1</sup> barely. When excluding FSU average annual increases for absolute consumption per decade of 3.7%, 0.65%, 1.54%, and 1.82% are observed for respectively the 1970s, 1980s, 1990s, and 2000s. Consumption per hectare shows similar trends, caused by developing countries phosphorus fertilizer application growing towards, or significantly beyond European and US levels, possibly indicating over-application. In contrast per capita fertilizer consumption between 1970-2009 fluctuated between 2.1 and 2.8 kg P capita<sup>-1</sup> with a 2.6 kg P capita<sup>-1</sup> average (figure 3), despite average global food consumption rising from 2200 to 2800 kcal capita<sup>-1</sup> day<sup>-1</sup> between 1960-2009 (FAO 2011f).



Figure 3 – Global phosphorus fertilizer consumption 1961-2009 excluding FSU in kilogram P capita<sup>-1</sup> (left) and in kilogram P hectare<sup>-1</sup> agricultural area (right). Source: this study.

#### 4.5 Food calorie to fertilizer demand parameter

Parameter a of demand equation (3) was estimated. It converts food calories into phosphorus fertilizer demand and is assumed to be constant given observed stability from 1970-2009 in phosphorus fertilizer consumption per capita (figure 3, section 4.4). The global dataset excluding FSU was applied to eliminate the one-off effect of the breakup event. The non-linear estimation, including -0.076 demand elasticity  $\sigma$ , an estimated 1.18 for parameter  $\theta$  from the average fertilizer to non-fertilizer ratio, and a kcal capita<sup>-1</sup> time series (FAO 2011f), yielded a  $7.8 * 10^{-9}$  parameter *a* value. To validate the relationship first a one-sample Kolmogorov-Smirnov test was conducted failing to reject the null hypothesis that the data followed the normal distribution (Difference = 0.093, 0.141, 0.72 respectively for variables D, E, N, with N = 49 each, and p > 0.05 each). Subsequently, the null hypothesis "Non-existence of a distribution of phosphorus demand D, as dependent on population N, E, and fertilizer prices  $p_t$  to the power of parameter  $\sigma$  multiplied by constants a and  $\theta^{"}$  was tested. The non-linear procedure yielded a value smaller than the  $\alpha$  = 0.05 critical level rejecting the null hypothesis, and a correlation R<sup>2</sup> of 0.93 with 48 degrees of freedom, on the basis of which estimated parameter values were adopted. In figure 4 estimated phosphorus demand from 1961-2009 using the parameterized equation (3) is shown.



Figure 4 - Historic fertilizer phosphorus consumption (solid line) compared with estimated consumption (dashed line) for total world (left) and world excluding FSU (right) from 1961-2009. Values measured in 46% P. Source: own compilation based on UN (2010) and FAO (2011d,e,f).

#### 4.6 Model production inputs data

Phosphate rock input  $\zeta_i$  and sulfuric acid input ratios  $\eta_i$  in equation (4) differ for each country. To analyse the effects on the amount of rock processed due to changing P<sub>2</sub>O<sub>5</sub> content, and sulfuric

acid use by CaO rock content, data was obtained for 108 mines and phosphoric acid producing operations in 24 countries (Fertecon et al. 1983). The analysis did not yield significant statistical results to enable country by country variation for parameters  $\zeta_i$  and  $\eta_i$  depending on rock quality. Therefore a fixed value was used for each country at 3.8, 0.44, 0.22 for respectively  $\zeta$ ,  $\eta$ ,  $\vartheta$ , as input in tons of phosphate rock, sulphur, and ammonia, per ton DAP produced (Mew and Marlow 2010; Weisz et al. 2008).

#### 4.7 Model fertilizer production costs data

To initialize equation (7) data for DAP fertilizer prices and ammonia, sulfuric acid, phosphate rock, and conversion cost was gathered (Weisz et al. 2008; World Bank 2011). The price series showed fairly constant levels close to marginal production cost as expected in a competitive market, except for periods of insufficient marginal supply under rising demand, where phosphate rock import cost of non-integrated fertilizer producers govern prices. For instance, between 2007-2009 fertilizer prices of the largest phosphate rock importer rose from 280 to 1000 USD ton<sup>-1</sup> DAP (Rawashdeh and Maxwell 2011). Only a small market share was affected, however, as 70% of phosphate fertilizer producers are vertically integrated. Therefore, rent taking was excluded and the initial model period was based on 2006/2007 fertilizer market cost data. When individual country values were absent geographically close country values were applied. To provide an upper phosphate rock mining cost limit, inflation corrected values of 100 and 300 USD ton<sup>-1</sup> phosphate rock was applied for respectively known and potential reserves. Informed by current costs and the most expensive reported cost figure for a non-producing underground phosphorus mine (Fertecon 1983; Fantell et al. 1988)

#### 4.8 Model scenario analysis

Several model runs were made based on four scenarios simulated to 2200 to assess implications of known and potential phosphate rock reserves variation (section 3.1), and use reduction and recycling measures (section 3.6). The scenarios are 1) known reserves 2) known reserves including recycling, 3) known and potential reserves, 4) known and potential reserves including recycling. In addition it was assumed for scenario's 2 and 4 that a central planner attempts to maintain respectively 75 and 100 years of phosphate rock reserves for all countries except Morocco. Also constraints were set for each country to look forward 5 years in time with a minimum of 20 years reserves available before investment takes place.

#### 5. Result and discussion

#### 5.1 Global phosphorus flows in 2009

The 2009 flow assessment summarized in figure 5 shows total phosphate rock extracted at 22.8 Mt elemental phosphorus, of which 21.4 Mt converted into phosphoric acid for the production of 17.5 Mt fertilizer phosphorus, 1.1 as livestock feed additives, 1.1 in other industrial uses, 1.1 in detergent production, 0.2 in food and beverage production, and 0.1 in pesticide production. Due to a lack of recovery 6.8 Mt is estimated to end up in landfills and waterways, and 13.7 Mt lost from agricultural and 12 Mt from non-agricultural soils through water erosion. The results show agricultural inputs-outputs to be balanced at a net +0.7 Mt flow, in contrast to previous studies (Smil 2000; Liu et al. 2008), primarily due to inorganic phosphorus inputs (table 4). Management of agricultural systems using external inputs on aggregate thus appears to provide compensation for erosion losses, which would imply that phosphorus losses are less of a problem then sometimes assumed, as long as phosphorus fertilizer inputs can be maintained. However, from a bio-availability perspective, a net agricultural ecosystem loss of 8.1 Mt inorganic phosphorus and a net gain of 8.8 Mt organic phosphorus is observed, indicating slowly decreasing phosphorus soil bio-availability. The total organic and inorganic agricultural soil pool was estimated at 6 and 36 Gt phosphorus respectively (Smil 2000), due to which present rates of bio-availability change will only have substantial impact on aggregate over centuries.

Agricultural Phosphorus		Total		Inorganic		Organic
Balance (Mt P)	Inputs	Outputs	Inputs	Outputs	Inputs	Outputs
Fertilizer inputs	16.7		16.7		0	
Pesticide inputs	0.1		0.1		0	
Crop losses & residues	3.8		1.6		2.2	
Animal & Human Manure	30.4		17.4		13.0	
Food waste recycling	0.8		0.3		0.5	
Crop uptake		12.5		12.5		0
Animal Grazing		24.9		24.9		0
Water Erosion		13.7		6.8		6.9
Total	51.8	51.1	36.1	44.2	15.7	6.9

Table 4 – Estimated agricultural phosphorus balance for 2009

Source: this study based on various data sources; see section 3.5



Figure 5 – Global Phosphorus flows in 2009. Total content displayed without brackets and organic content within brackets. Source: this study based on various data sources; see Section 2.1.

#### 5.2 Potentials of recycling and use reduction

Informed by our phosphorus flow assessment eleven reduction and recycling measures were estimated in non-agricultural, food processing, and agricultural sectors (section 3.6). Their potential and cost, summarized in table 5, provides a global reduction potential of 12.95 Mt phosphorus year<sup>-1</sup>, of which 6.88 Mt from use reduction and 6.07 Mt from recycling.

Technology/Practice	Type of	Phosphorus	Potential	Total	Economic	Sources
	measure	Flow Affected	reduction	flow	Cost*	
			(Mt/yr)	(Mt/yr)	(USD/ton)	
Beverage acidulation agent substitution **	Use reduction	Non-agriculture, industrial use	0.1	0.1	0	Authors' estimate
Phosphorus substitution in detergents**	Use reduction	Non-agriculture, detergents	0 or 1.1***	1.1	0	Authors' estimate based on European Commission (2010), Walsh (2010)
Food waste loss reduction in food processing**	Use reduction	Agriculture, harvested crops	0.25	0.95	0	Authors' estimate based
Food waste loss reduction in distribution**	Use reduction	Agriculture, food products	0.05	0.25	0	on Lee and Willis (2010)
Food waste loss reduction by Consumers**	Use reduction	Agriculture, consumption	0.21	1.07	0	
No-Till Farming > 200 ha**	Use reduction	Soil erosion	1.75	13.7	0	Authors' estimate based
No-Till Farming < 200 ha	Use reduction	Soil erosion	1.75	13.7	1030	on Epplin (2008), FAO (2010)
Phosphorus retrieval from wetland biomass	Recycling	Soil erosion	2.50	13.7	7280	Author's estimate based on Seymour (2009)
Biofertilizer application**	Use reduction	Agriculture,	1.67	16.7	0	Jilan et al. (2007), Zabihi et al. (2011)
Non-Food commodities Phosphorus Recycling	Recycling	Agriculture, food products	0.24	0.30	7030	Gebrezgabher et al. (2010)
Food Waste Phosphorus Recycling	Recycling	Agriculture, food products	1.23	1.76	1000	Westeinde (2009)
Phosphorus wastewater recycling	Recycling	Agriculture, sewage	2.1 or 2.8****	4.2 or 5.3****	6750	Seymour (2009)
TOTAL			12.95			

Table 5 – Potential and cost of phosphorus use reduction and recycling measures

\*Cost estimate excludes in-direct cost effects due to human behavioral change

\*\*Cost neutrality is assumed based on saved input quantities compensating for necessary investments

\*\*\*Varying due to the implementation of wastewater recycling versus detergent phosphorus reduction

\*\*\*\*Human excreta ending up in wastewater plants with variance by detergent phosphorus reduction

#### 5.3 Phosphorus availability projection

#### 5.3.1 Demand forecast

Simulated phosphorus demand excluding any recycling or use reduction grows because of exogenous population increases to 9 billion in 2045 and 10 billion in 2080, assuming constant population afterwards. Under these assumptions elemental phosphorus demand grows from 21.3 to 30 Mt, of which non-fertilizer use from 3.8 to 5.4 Mt, from 2009-2080, similar to other estimates (Cooper et al. 2011; Mew 2011; Van Vuuren et al. 2010). When translated to 46% phosphorus fertilizer equivalent this yields 53.5 and 11.8 Mt of fertilizer and non-fertilizer, and as total phosphate rock 250 Mt, shown in figure 6. The outcome is primarily influenced by the underlying per capita relationship of demand equation (3), whereas 1970-2009 consumption averaged 2.6 kg P capita<sup>-1</sup> year<sup>-1</sup> (section 4.4). When multiplying 2.6 by 3 billion additional people an 7.8 Mt additional elemental phosphorus consumed per year is obtained.



Figure 6 - Result demand simulation from 2010 to 2200 without supply constraint for fertilizer equivalent (fertilizer + non-fertilizer use), on left as ton of fertilizer (46% P), and on right as phosphate rock. Source: this study.

#### 5.3.2 Model results for phosphorus availability

The scenario results, displayed in figure 7 and table 6, show conservative reserve assumptions to induce production decline early 21<sup>st</sup> century (scenario 1). Recycling and use management efforts shift the decline substantially, in our simulation by over 50 years (scenario 2). The price path in both scenario's shows a gradual rise towards a fertilizer price of 400 USD ton<sup>-1</sup> of DAP, set by the constraint of 100 USD ton<sup>-1</sup> phosphate rock (section 4.7). The shift comes at substantial cost to the central planner whereas 7.5 Mt phosphorus measures at 1030 and 7030 USD ton<sup>-1</sup> cause an annual 24 billion USD burden four times higher than simulated phosphate rock fertilizer industry revenues (scenario 2).

In case of wider reserve boundaries ample supply is available up to end 22<sup>nd</sup> century (scenario 3), albeit at higher cost with prices rising to 800 USD ton<sup>-1</sup> DAP, approximately 2.5 times current cost levels. The primary reason is depletion of small production sites causing costs to rise rapidly to the assumed 300 USD ton<sup>-1</sup> upper limit of phosphate rock for potential reserves (section 4.7). Introducing recycling and use reduction in scenario 4 causes availability of supply well into the 23<sup>rd</sup> century, and prices to rise less rapidly to 450 USD ton<sup>-1</sup> DAP, as costly to exploit reserves remain underground. Only cost neutral measures are undertaken due to which the central planner's burden remains low. In all scenarios Morocco has a lower cost profile then most other producers, with beneficiated phosphate rock costs remaining below 173 USD ton<sup>-1</sup> providing large profits.



Figure 7 - Scenario results for known reserves (top left), known reserves including recycling (bottom left), known and potential reserves (top right), known and potential reserves including recycling (bottom right). Red line: historic data points (1961-2009), black line: phosphorus from produced reserves, dotted line: substitute use reduction and recycling phosphorus. Source: this study

Scenarios	Known reserves (1)	Known reserves &	Known + Potential	Known + Potential							
		recycling (2)	reserves (3)	reserves & recycling (4)							
Demand	Peaks as	Can be met until 2090, declines	Maintained at 250 Mt with	Maintained at 250 Mt with							
development	production declines	and stabilizes around 100 Mt in	slight decline to 240 Mt in	slight decline to 240 Mt in							
		22 <sup>nd</sup> century	22 <sup>nd</sup> century due to price	22 <sup>nd</sup> century due to price							
			elasticity	elasticity							
Production	Peaks at 235 Mt around	Peaks around 2020 as recycling	Sufficient to meet demand	Sufficient to meet demand							
development	2050 declining to	measures kick-in, with second	beyond 22 <sup>nd</sup> century	beyond 23 <sup>nd</sup> century							
	marginal levels early 22 <sup>nd</sup>	peak and decline in 2090									
	century										
Recycling/use	n.a.	Both cost neutral and cost	n.a.	Cost neutral effects are							
reduction effects		positive recycling and reduction		introduced after 2025,							
		is fully used shifting production		sufficient to maintain reserve							
		to later in the 21 <sup>st</sup> century		stocks							
Price	Rises to 400 USD per	Rises to 400 USD per ton DAP	Rises to 800 USD per ton of	Rises to 450 USD per ton of							
development	ton DAP	with temporary decline around	DAP	DAP, with temporary decline							
		2050s as costly producers go		around 2050s as costly							
		offline		producers go offline							
Moroccan	Starts to dominate supply	Starts to dominate supply after	Dominates supply after	Dominates late 21 <sup>st</sup> century							
production	after 2070s	2060s	2070s, 60%+ supply around	with 70% share in 2100 and							
share			21 <sup>st</sup> century, 90%+ at end	87% in 2200							
			22 <sup>nd</sup>								

Table 6 – Results of model scenarios

#### 5.4 Discussion

We quantified global phosphorus flows in 2009 finding aggregate agriculture inputs of phosphorus fertilizers, crop residues, and animal manure to be balanced with crop and animal outputs and water erosion losses. Key uncertainties are erosion levels, phosphorus bio-availability, and animal manure fluxes. In previous studies constant erosion rates were applied across global agricultural areas, leading to an overly negative perspective. Data shows large agricultural areas to be in a constant or increasing productive state, indicating absence of erosion. We corrected this by applying erosion estimates only to agricultural areas with demonstrated productivity loss. Our exclusion of microbial-soil-plant interactions simplifies ecosystem to inflows and outflow balancing, while in reality soils contain "pools" of organic and inorganic phosphorus. The indicated inorganic loss in agricultural ecosystems (section 5.1) will plausibly be lowered due to the microbial turnover of organic into inorganic. Our quantification of animal manure fluxes itself has a high certainty because animal numbers, manure output, and phosphorus content are well documented, but flow assumptions contain a high error margin by assuming full soil application of animal manure, while a portion may end up in landfills, or is redirected to other uses.

Recycling and use reduction measures were quantified informed by flow and cost assessments. Such an approach can provide a quantitative basis to implement a phosphorus use and recycling strategy, when translated to country and regional levels, and when uncertainty of key assumptions is narrowed down. For example, assuming no-till farming applicability to half of cropland in 4000+ USD capita<sup>-1</sup> countries. Regardless, our preliminary analysis shows substantial potential for use reduction and recycling. The recycling measures are in most cases too costly because phosphate rock based supplies are cheaper, even when assuming triple inorganic fertilizer cost. In this respect, impact use reduction warrants more attention given low cost availability, with behavioural change and absent regulation being main barriers to implementation. However, external phosphorus pollution costs such as eutrophication and soil erosion were ignored which could substantially change the market assessment. Clean-up cost of phosphorus pollution to freshwater bodies from wastewater treatment discharge has been estimated at 57,000 USD ton<sup>-1</sup> phosphorus (Hernandez-Sancho et al. 2010; Molinos-Senante et al. 2011). Erosion control benefits in prevention of agricultural productivity loss have been estimated for Europe at 650 million USD year-1 (Kuhlman et al. 2010). Use reduction and recycling measures can thereby provide significant indirect benefits or prevention of costs which

affect cost assumptions. For instance, our zero cost assumptions for use reduction measures (table 11) could become positive benefits, when externalities are taken into account.

The examined measures were used in a supply-demand model with key uncertainties due to assumed reserve levels, production mechanisms, and demand changes (sections 1.1, 3.1, 3.2). The established relationship between population growth, food consumption in kcal, and phosphorus fertilizer consumption per capita, is predicated on observed stability of the latter factor when excluding the FSU (figure 3). Since global food production per capita increased significantly the stability indicates gains in phosphorus fertilizer productivity. The ascertained relationship could be altered if global productivity growth slows down or accelerates, for instance due to use precision in countries such as India which plausibly over-applies fertilizers. Also a step wise change in kcal food consumed due to economic growth in developing countries could have an impact, for instance meat consumption growth in India is affecting agricultural expansion and fertilizer consumption. Detailed country analyses for phosphorus are crucial, especially given large data uncertainty in the last few years, with large changes in China where phosphate rock production has grown from a 22% to a 40% global share between 2006-2012, and with phosphate fertilizer consumption growth in the order of 20%+ in both countries.

In terms of model outcomes we observe only conservative reserve assessments to lead to phosphorus scarcity, whereas resources exist to supply the world at least up to the 22<sup>nd</sup> century, as long as economic and technical extraction is enabled. There are three reasons to be positive about such developments. First, congruence between different geological reports on wide reserve boundaries, in this paper denoted as potential reserves. Second, mechanics of phosphate rock mining are such that decreasing deposit quality results in gradual instead of sudden cost increases, not to be confused with temporary supply-demand price imbalances. Since the majority of phosphate rock exists underground in an ore grade range of 6%-32% close to the surface it is plausible that processing costs will only double to triple on average. Third, advances in technology beyond the wet acid process used in 95% of operations are likely to unlock more resources. Specifically JDC Phosphate (2010) developed technology enabling extraction of high magnesium content deposits. Notwithstanding phosphate rock availability, introducing use reduction and recycling shows substantial positive benefits on resource base longevity, and can also have positive price depressing effects by pushing phosphate rock producers with high marginal costs out of the market.

#### 6. Conclusions

In this article we explored global flows of phosphorus, potential measures to reduce and redirect these flows, and the implications of these measures on phosphorus availability. The analysis leads to the following conclusions:

- Agricultural phosphorus inputs and outputs are found globally to be balanced on average, in contrast large net losses occur in non-agricultural systems. Main loss mechanisms are water erosion and land-filling; key uncertainties are water erosion rates, phosphorus bio-availability and manure flows.
- To close agricultural phosphorus cycles attention needs to be paid to organic and inorganic phosphorus. Plants overtly take up inorganic phosphorus and convert it into organic phosphorus. A net loss of inorganic and net gain in organic phosphorus was estimated for the global agricultural system.
- It can be assumed that phosphate rock supplies will be able to meet growing demand in the 21<sup>st</sup> and maintain high consumption levels throughout the 22<sup>nd</sup> century. Our confidence stems from the phosphate rock resource base, which enable much larger reserves to be exploited than assumed today.
- Substantial measures exist that can substitute over half of phosphate rock mined today. About half of the potential can be obtained through products use and food waste reduction, the other half through waste streams and waterways phosphorus recycling. A thorough cost estimate of externalities including eutrophication and erosion is warranted to fully assess the economics.
- The introduction of recycling and use reduction can substantially improve the longevity of the resource base. In case of conservative known reserves phosphorus availability is extended under growing demand to the end of the 21<sup>st</sup> century, and when including potential reserves beyond the 23<sup>rd</sup> century.
- There is a mismatch between quantitative research performed on specific measures, and their economic and flow potential. The bulk of conducted studies focus on technological measures prominently waste water recycling. In contrast, the greatest

potential for closing phosphorus cycles lies in agriculture, waterway wetland recovery, non-food substitution, and food waste reduction.

#### Acknowledgements

The authors would like to thank three anonymous reviewers for providing substantial critical comments which helped to improve the quality of our paper.

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#### Appendix A – supplementary material

Country	Known		Potential		Demons	strated	Sources
	Reserv	/es	Reser	ves	Resource	ces*	
	Mt	%P₂O	Mt	%P <sub>2</sub> O <sub>5</sub>	Mt	%P <sub>2</sub> O <sub>5</sub>	
Algeria	260	24%	n.a.	n.a.	2000	24	Kauwenbergh (2010), Mezghache et al. (2004)
Angola	n.a.	n.a.	130	35%	710	35%	Kauwenbergh (2010), Van Straaten (2002)
Australia	67	24%	182	21.3%	1014	22%	AIMR (2010)
Brazil	900	8.6%	784	9.2%	289	7.7%	Appleton and Notholt (2002) Kauwenbergh (2010), Mining Almanac (2011) Peroni et al. (2010)
Canada	n.a.	n.a.	5	23.4%	130	23.4%	Kauwenbergh (2010), Phoscan (2009)
China	2100	28%	2000	24%	16800	18%	Kauwenbergh (2010), Zhang et al. (2009)
Egypt	82	18%	n.a	n.a	3400	19%	Kauwenbergh (2010)
Finland	53	16.5%	110	16.5%	310	4.5%	Kauwenbergh (2010)
Israel	130	32%	250	27.5%	1600	27.5%	Kauwenbergh (2010), Notholt et al. (1989)
Jordan	1460	19%	370	26.5%	1000	19%	Kauwenbergh (2010), Jordan Phosphate Mines Company (2011)
Kazakhstan	266	10.6%	209	10.6%	3100	25%	Cook and Shergold (1986), Kauwenbergh (2010), Sunkar Resources (2011)
Morocco	5700	28.5%	45300	28.5%	119	28.5%	Kauwenbergh (2010), Notholt et al. (1989)
Peru	247	17.3%	569	17.3%	5625	8%	Notholt et al. (1989), Appleton and Notholt (2002)
Russia	1580	12%	355	13%	3600	10%	Kauwenbergh (2010)
Saudi Arabia	233	19.8%	503	18.1%	3544	20%	Kauwenbergh (2010), Riddler et al. (1989)
Senegal	62	25.9%	90	25%	98	22%	Kauwenbergh (2010),
South Africa	650	6.9%	975	6.9%	6023	6.5%	Kauwenbergh (2010)
Syria	400	24%	n.a.	n.a.	2000	19%	Kauwenbergh (2010)
Тодо	n.a.	n.a.	34	25%	1000	25%	Kauwenbergh (2010)
Tunisia	153	18%	n.a.	n.a.	1100	12%	Kauwenbergh (2010)
United States	1400	30%	2000	30%	49000	30%	Kauwenbergh (2010)
World Total	15743		53866		102462		This Study

Table 7 - Phosphate rock per resource category in Mt of ore and  $P_2O_5$  content per country and world total.

\*If demonstrated resource figures (measured or indicated) are available they are displayed, otherwise inferred resources are shown.

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#### Appendix B – supplementary material

	Harvested Unit			Estimated crop Resid	Total P delivery to	
	Mt Fresh Matter	Mt Dry Matter	Mt P flow	Mt Fresh matter	Mt P flow	food & agricultural system
Cereals	2494	2192	6.57	3288	3.24	9.81
Sugar Crops	1889	586	0.62	461	0.87	1.49
Roots and						
tubers	736	148	0.10	221	0.20	0.31
Vegetables	1011	101	0.11	165	0.11	0.23
Fruit	594	89	0.12	146	0.12	0.23
Pulses	64	61	0.32	63	0.10	0.42
Oil Crops	162	119	0.12	110	0.12	0.24
Other crops	41	33	0.04	84	0.08	0.12
Total Crops	6992	3329	8.00	4163	4.5	12.50
Meat		280	0.70			0.70
Milk		687	0.62			0.62
Eggs		68	0.01			0.01
Fish		148	0.41			0.41
Total animals		1183	1.74			1.74
Total animals +	crops		9.74			14.24

#### Table 8 - Phosphorus flow from harvested crops, crop residues, and consumed animals and animal products in 2009

Source: This study based on FAO (2011b), FAO (2011c), USDA (2011), Williams (2007) using the methodology from Smil (2000).

Table 9 -	Estimated 2009	losses of al	lobal phos	phorus flow in	n food & fe	ed production

Production stage	loss average	Associated Flows (c)	Food production flows (b)	Total 2009 P flow loss (d)
	percentage (a)		(Mt of phosphorus)	(Mt of phosphorus)
Field Harvest	6.2%	X <sub>21</sub>	8.00	0.50
Postharvest handling & storage	7.5%	X <sub>23</sub>	7.50	0.56
Processing and packaging	11.7%	$X_{26} + X_{39} + X_{25} + X_8$	6.20	0.70
Supermarket retail	4.5%	$X_{26} + X_{39} + X_{25} + X_8 - 0.7$	5.50	0.25
Consumer handling	20.0%	X <sub>31</sub>	5.25	1.07
TOTAL LOSS				3.08

Source: (a) Gustavsson et al. (2011) (b) this study table 3 (c) this study figure 3, (d) this study.

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Type of Animal Animal Count (a)		Manure production (b) Manure P content (c)		Total 2009 P flow (d)
	(millions)	(DM in kg year⁻¹)	(g per kg DM)	(Mt of phosphorus)
Cattle	1380.2	1405	7.2	14.0
Sheep	1077.2	144	5.6	0.9
Pigs	941.8	157	16.9	2.5
Goats	879.7	124	5.6	0.6
Buffaloes	187.9	1015	7.2	1.4
Turkeys	458.0	51	18.7	0.4
Chickens	18631.4	22	20.3	8.3
Ducks	1175.6	7	9.7	0.1
Geese & guinea fowls	357.1	15	9.7	0.1
Other Animals	170.7	146	5.6	0.1
TOTAL				28.3

Source: (a) FAO (2011a), (b) IPCC (1996), (c) Barnett (1994) and Defra (2010), (d) this study.

#### Table 11 - Estimated 2009 global phosphorus erosion loss estimate

Type of land	Land area (a) (Million ha)	Degraded land (a) (percentage)	Erosion rate (tonnes ha <sup>-1</sup> year <sup>-1</sup> )	Soil phosphorus (d) content (kg P ton <sup>-1</sup> soil)	Total 2009 P erosion flow (e) (Mt P per year)
Cropland	7629	22.1%	35* (b)	0.6	9.33
Pastureland	2004	19.6%	20 (c)	0.6	9.01
Non-agricultural land	3825	17.5%	20 (c)	0.6	16.0
TOTAL					34.3
TOTAL assuming 25% re-deposition (c) 25.					25.7

Source: (a) Bai et al. (2003), (b) Montgomery (2007), (c) Smil (2000), (d) Fabre et al. (2006) Turner et al. (2003), (e) this study

\* Montgomery's (2007) analysed 448 cropland soil erosion studies with a mean 3.94 mm year<sup>-1</sup> (42 tonnes of soil ha<sup>-1</sup> year<sup>-1</sup>) erosion rate, and median of 1.54 mm year<sup>-1</sup>, indicating outliers. Paskett and Philoctete (1990) was found to be a source of bias whose removal yielded a corrected mean 2.95 mm year<sup>-1</sup>(35 tonnes of soil ha<sup>-1</sup> year<sup>-1</sup>).

	Table 12 - Estimated of	alobal phosphol	rus erosion loss	s estimate con	nparison with	other studies
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Study Reference	Study type	Area of estimate	Year of estimate	Erosion estimate (Mt P per year)
Liu et al. (2008)	soil erosion rates to area based calculation	Crops & Pasturelands	2003	36.5
Smil (2000)	soil erosion rates to area based calculation	Crops, Pasture, Non-Agriculture	2000	20.0
Compton (2000)	Meta-assessment from estuary measurements	Crops, Pasture, Non-Agriculture	2000	17.7-30.4
Tappin (2002)	Meta-assessment from estuary measurements	Crops, Pasture, Non-Agriculture	2002	22.0
This study	soil erosion rates to area calculation	Crops, Pasture, Non-Agriculture	2009	25.7

#### Table 13 - bio-availability of phosphorus from plant matter decomposition and excreta

Phosphorus flow	Assumptions	flows (e)	Total	Inorganic	Organic
			(Mt P/yr)	fraction	fraction
				(Mt P/yr)	(Mt P/yr)
P in agricultural soils	50% bio-available to plants and $50%$ immobile (a)	X <sub>40</sub>	12.0	6.0	6.0
P in non-agricultural soils		X <sub>38</sub>	13.7	6.85	6.85
Decomposing plant matter	40% rapidly bio-available, 60% slowly via mineralization (b)	X <sub>20</sub>	3.8	1.5	2.3
		X <sub>28</sub>	0.8	0.3	0.5
Human manure	50% inorganic content, 2/3rds phosphorus excreted (c)	X <sub>34</sub> , X <sub>35</sub>	2.8	1.4	1.4
Human urine	100% inorganic content, 1/3rds phosphorus excreted (c)	X <sub>34</sub> , X <sub>35</sub>	1.4	1.4	0.0
Non-ruminant animal manure	50% inorganic content, 2/3rds phosphorus excreted (c)	X <sub>17</sub>	7.6	3.8	3.8
Non-ruminant animal urine	100% inorganic content, 1/3rds phosphorus excreted (c)	X <sub>17</sub>	3.8	3.8	0
Ruminant animal manure	50% inorganic content, all phosphorus excreted in manure (d)	X <sub>17</sub>	17.0	8.5	8.5
Ruminant animal urine	No phosphorus is excreted in urine (d)	X <sub>17</sub>	0.0	0.0	0.0

Source: (a) Smil (2000), Turner et al. (2003), (b) Dzotsi et al. (2010), Magid et al. (1996), Lupwayi et al. (2007), (c) Karak and Bhattacharyya (2011), (d) Barnett (1994), Bravo et al. (2003), (e) this study figure 3.

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