Supplementary File – for Online Publication Only

**Closing the phosphorus cycle in a food system: insights from a modelling exercise**H.R.J. van Kernebeek1, S.J. Oosting1, M.K. van Ittersum2, R. Ripoll Bosch1, and I.J.M. de Boer1

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Supplementary Material S1 Available crop products for humans, cows and pigs

Crop products available in this study, and an overview of whether or not products are edible or restricted for humans, cows and pigs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | Humans | Cows | Pigs |
| Industrial food processing |  |  |  |  |
| *Dry milling of wheat* |  |  |  |  |
|  | Wheat middlings | n.c. | restr1 | restr1 |
|  | Wheat germ | n.r. | restr1 | restr1 |
|  | Wheat bran | n.r. | restr1 | restr1 |
|  | Wheat flour | n.r. | restr1 | restr1 |
| *Peeling of potato* |  |  |  |  |
|  | Potato tuber | n.r. | n.r. | n.r. |
|  | Potato peel | n.c. | restr1 | restr1 |
| *Sugar beet processing* |  |  |  |  |
|  | Sugar | restr | restr1 | restr1 |
|  | sugar factory lime | n.c. | n.c. | n.c. |
|  | Sugar beet molasses | n.c. | restr1 | restr1 |
|  | Sugar beet pulp | n.c. | restr1 | restr1 |
| *Crushing of rapeseed* |  |  |  |  |
|  | Rapeseed oil | n.r. | n.r. | restr1 |
|  | Rapeseed meal | n.c. | restr1 | restr1 |
|  |  |  |  |  |
| Industrial feed processing |  |  |  |  |
| *Grinding of wheat* | Ground wheat grain | n.c. | restr2 | restr2 |
| *Chopping of wheat straw* | Chopped wheat straw | n.c. | n.r. | n.c. |
| *Heating of potatoes* | Potatoes | n.c. | restr2 | restr2 |
| *Cutting of sugar beet* | Cut sugar beet | n.c. | restr2 | restr2 |
| *Cutting of sugar beet tops & tails* | Cut sugar beet tops & tails | n.c. | restr2 | n.r. |
| *Grinding of rapeseed* | Ground rapeseed | n.c. | restr2 | restr2 |
| *Chopping of rapeseed straw* | Chopped rapeseed straw | n.c. | restr2 | n.c. |
|  |  |  |  |  |
| Feed or food processing |  |  |  |  |
|  | Brown beans | n.r. | restr1 | restr1 |
|  |  |  |  |  |
| Ensilaging |  |  |  |  |
|  | Silage maize | n.c. | n.r. | n.c. |
|  | Silage grass | n.c. | n.r. | n.c. |
|  |  |  |  |  |
| No processing |  |  |  |  |
|  | Fresh grass | n.c. | n.r. | n.c. |

Note: n.c. = not consumed, we did not allow this product to be consumed; n.r. = not restricted, this product could be consumed without dietary restriction, restr = restriced, consumption of this product was restricted; 1Van Kernebeek *et al.* (2016); 2Section Animal production system in Supplementary Material S4.

Supplementary Material S2. Waste of crop and animal products along the chain

Waste of crops and crop products are provided in Table S1. In addition, during animal processing we assumed 6% waste of meat and 2% waste of milk (Gustavsson *et al.*, 2011). Moreover, during human consumption we assumed 15% waste of meat and 8% waste of milk (Gustavsson *et al.*, 2011).

Table S1 Post-harvest waste (%) of crop products during various steps in the food and feed chain

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | | |  | | | Post-harvest storage | Processing | Human consumption | Animal husbandry |
| Prior to processing | | | |  | | |  |  |  |  |
|  | | | | Wheat grain | | | 4 |  |  |  |
|  | | | | Wheat straw | | | 5 |  |  |  |
|  | | | | Potato | | | 9 |  |  |  |
|  | | | | Sugar beet | | | 9 |  |  |  |
|  | sugar beet tops&tails | | | | | | 5 |  |  |  |
|  | | | | Rapeseeds | | | 1 |  |  |  |
|  | | | | Rapeseed straw | | | 5 |  |  |  |
|  | | | | Beans | | | 1 |  |  |  |
|  | | | |  | | |  |  |  |  |
| Industrial food processing | | | | | |  |  |  |  |  |
| *Dry milling of wheat* | | | |  | | |  |  |  |  |
|  | | | | Wheat middlings | | |  | 5 | 27 | 2 |
|  | | | | Wheat germ | | |  | 5 | 27 | 2 |
|  | | | | Wheat bran | | |  | 5 | 27 | 2 |
|  | | | | Wheat flour | | |  | 5 | 27 | 2 |
| *Peeling of potato* | | | |  | | |  |  |  |  |
|  | | | | Potato tuber | | |  | 15 | 23 | 22 |
|  | | | | Potato peel | | |  | 15 |  | 10 |
| *Sugar beet processing* | | | | | |  |  |  |  |  |
|  | | | | Sugar | | |  | 15 | 23 | 2 |
|  | | sugar factory lime | | | | |  | 15 |  |  |
|  | | | | Sugar beet molasses | | |  | 15 |  | 2 |
|  | | | | Sugar beet pulp | | |  | 15 |  | 7 |
| *Crushing of rapeseed* | | | |  | | |  |  |  |  |
|  | | | | Rapeseed oil | | |  | 5 | 5 | 2 |
|  | | | | Rapeseed meal | | |  | 5 |  | 2 |
|  | | | |  | | |  |  |  |  |
| Industrial feed processing | | | | | |  |  |  |  |  |
| *Grinding of wheat* | | | Ground wheat grain | | | |  |  |  | 2 |
| *Chopping of wheat straw* | | | | Chopped wheat straw | | |  |  |  | 24 |
| *Heating of potatoes* | | | | Potatoes | | |  |  |  | 22 |
| *Cutting of sugar beet* | | | | Cut sugar beet | | |  |  |  | 7 |
| *Cutting of sugar beet tops & tails* | | | | Cut sugar beet tops & tails | | |  |  |  | 29 |
| *Grinding of rapeseed* | | | | Ground rapeseed | | |  |  |  | 2 |
| *Chopping of rapeseed straw* | | | | Chopped rapeseed straw | | |  |  |  | 24 |
|  | | | |  | | |  |  |  |  |
| Feed or food processing | | | | |  | |  |  |  |  |
|  | | | | Brown beans | | |  |  | 5 | 15 |
|  | | | |  | | |  |  |  |  |
| Ensilaging | | | |  | | |  |  |  |  |
|  | | | | Silage maize | | |  |  |  | 12 |
|  | | | | Silage grass | | |  |  |  | 19 |

Note: based on Remmelink *et al.* (2012) and Gustavsson *et al.* (2011)

Supplementary Material S3 Crop fertilisation

Total amount of P required per ha for each crop rotation was computed from the P content of all crops in that rotation and assumed unavoidable losses through leaching and run-off (Eq. 1) (Table S2). Wheat and maize stubble, potato haulms, sugar beet leaves and bean straw were not included, as we assumed that these parts of the crops stayed behind on the field as a source of P for the subsequent crop.

Eq. 1

Where TRi,l is the total requirement of P per ha (in kg ha-1), for crop rotation (i) on land type (l), based on the sum of all harvested products (j) from that rotation, including main and co-products (Supplementary Material S1); Y is the fresh matter yield of a harvested product (ton ha-1) (Online resource I in Van Kernebeek *et al.,* (2016)), DM is the dry matter content of a harvested product (Online Source I in Van Kernebeek *et al.,* (2016)), Pcont is the nutrient content of a harvested product (kg ton-1 DM) (PDV, 2011), and UL is the unavoidable P loss (kg ha-1) through leaching and run-off, which was assumed 2.2 kg P ha-1 on all soil types and crop rotations (Rijksoverheid, 2014).

Total amount of P required per ha for each crop rotation was provided by variable sources according to Eq. 2. For all recycled and organic fertiliser sources we assumed a P fertiliser replacement value relative to mineral fertiliser of 100% (De Haan and Van Geel, 2013, Severin *et al.*, 2014).

Eq. 2

Where TRi,l is the total fertiliser requirement of P for crop rotation (i) and soil type (l) (kg ha-1), MFi,l is the amount of P from mineral fertiliser (triple superphosphate) (kg ha-1). Mani,l,a,b is the volume of applied manure (ton DM) of manure type (b) produced in animal production system type (a). Manure types (b) differed in their nutrient concentrations. ManConca,b is the P concentration in manure (kg ton-1 DM) per manure type and animal production system type, VCRi,l,j is the amount of variable crop residue (ton DM) (j) left for crop rotation (i) on soil type (l). Nutrcontj, is the P content (kg ton-1 DM) in variable crop residue (j), Crpi,l,k is the volume of crop product (k) returned back to the land (ton DM ha-1), Nutrcontk is the P content of crop product (k) returned back to the land. HumanexcProcWateri,l  is the amount of P (kg ha-1) from recycled human excreta and industrial processing water. WasteAnimali,l is the amount of P (kg ha-1) from recycled waste of ASF, and Animalmeali,l is the amount of P (kg ha-1) from recycled animal meal. We did not allow fertilisation of grassland by crop residues or crop products returned back to the land.

Table S2 Total requirement (TR) of phosphorus (P) by crop rotation and soil type (kg ha-1)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | TR (kg ha-1) | | |  |  |
| Rotationa | Land type |  | P |  |  |  |
| G | Clay |  | 47 |  |  |  |
| M | Clay |  | 32 |  |  |  |
| WOWB | Clay |  | 25 |  |  |  |
| PWSW | Clay |  | 29 |  |  |  |
| PBSW | Clay |  | 25 |  |  |  |
| WOWBS | Clay |  | 26 |  |  |  |
| WOWBWP | Clay |  | 26 |  |  |  |
| G | Sand |  | 44 |  |  |  |
| M | Sand |  | 33 |  |  |  |
| WOWB | Sand |  | 24 |  |  |  |
| PWSW | Sand |  | 27 |  |  |  |
| PBSW | Sand |  | 24 |  |  |  |
| WOWBS | Sand |  | 24 |  |  |  |
| WOWBWP | Sand |  | 25 |  |  |  |
| G | Peat |  | 45 |  |  |  |

aG=grass, M=silage maize, W= wheat, O= oilseed, B=beans, P = potato, S = sugar beet.

Supplementary Material S4 Dietary requirements and intake restrictions of animals

Dietary requirements of each production unit (PU) regarding energy and protein intake, digestibility, structure and intake restrictions are described in detail in Van Kernebeek *et al.* (2016). In addition to these feed restrictions, we also accounted for feed restrictions for products that resulted from feed processing (Table S3).

Table S3 Feed restrictions per cow and pig production unit (PU) for products that resulted from feed processing

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | CowPU | PigPU | | Based on source |
| *Max. feed intake (ton DM) per animal PU year-1* |  |  | |  |
| Potato | 1.78 | 0.43 | | Feedipedia (2017) |
| Wheat grain | 3.67 |  | | Feedipedia (2017) |
| Sugar beet tops&tails | 1.23 |  | | Feedipedia (2017) |
| Rapeseed | 0.90 |  | Emanuelson *et al.* (1991) and Rymer and Short (2003) | |
| Rapeseed straw | 0.14 |  | | Vestjens (2017) |
|  |  |  | |  |
| *Max. fraction of total dry matter intake* |  |  | |  |
| Wheat grain |  | 0.4 | | Feedipedia (2017) |
| Rapeseed |  | 0.05 | | Pharazyn (2016) |
| Beans |  | 0.2 | | Feedipedia (2017) |
| Sugar beet | 0.4 | 0.056 | | Feedipedia (2017) |

Supplementary Material S5 Phosphorus retention in animals

P retention per animal PU was fixed, and was computed from P concentrations in body tissue and milk (Groenestein *et al.*, 2008, RVO, 2010), and production data (Van Kernebeek *et al.*, 2016) (Supplementary Table S4). P retention in body tissue per cowPU included retention in replaced dairy cow, surplus calves, and deceased replacement calves. Retention in human non-edible products was computed as ‘retention in body tissue minus retention in meat’. Retention in milk for human consumption was computed as ‘retention in raw milk minus retention in milk for replacement calves’.

Table S4 Production of meat and milk per pig and cow production unit (PU) per year, phosphorus (P) retention in body tissue, meat, milk, and human non-edible products, and P content of meat and milk

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Retention (kg) | | | Content (g kg-1)b | | |
|  | kga | P |  |  | P |  |  |
| PigPU |  |  |  |  |  |  |  |
| Body tissue |  | 2.0 |  |  |  |  |  |
| Of which meat | 171 | 0.51 |  |  | 3.0 |  |  |
| Of which human non-edible products |  | 1.5 |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| CowPU |  |  |  |  |  |  |  |
| Body tissue |  | 1.8 |  |  |  |  |  |
| Of which meat | 74 | 0.20 |  |  | 2.7 |  |  |
| Of which human non-edible products |  | 1.6 |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
| Raw milk | 8 120 | 7.9 |  |  |  |  |  |
| Of which for replacement calves | 79.2 | 0.08 |  |  |  |  |  |
| Milk for human consumption (FPCM) | 8 502 | 7.8 |  |  | 0.92 |  |  |

Note: FPCM = Fat and protein corrected milk.  aSee Online resources III and VI in Van Kernebeek *et al.* (2016) for herd composition and meat and milk production per animal PU, bP contents of meat were taken from RIVM (2013). P content of milk for human consumption was computed from production (kg) and P retention. P content of our milk for human consumption was comparable with the content of full fat milk as presented by the Dutch Food Composition Table NEVO (RIVM, 2013) (i.e. 1.02 g P kg-1).

Supplementary Material S6 Nutrient balances in crop processing

To assure nutrient balances in crop processes that involved separation of harvested crop into multiple crop products, we compared the nutrient content (kg of P and N per ton DM) of each harvested crop before processing (PDV, 2011) with the nutrient content of the sum of output products (including wastes), which we computed from nutrient content per ton dry matter (PDV, 2011) and output/input ratios (Van Kernebeek *et al.*, 2016). We computed N content as 16% of crude protein (PDV, 2012). In those cases where the nutrient content in the sum of output products was lower than in the harvested crop, we assumed that the remaining nutrients were dissolved in industrial processing water. This was the case for two processes, i.e. potato and sugar beet processing. During potato processing, 0.46 kg of 2.50 kg P ton-1 DM, and 1.42 kg of 16.32 kg N ton-1 DM potato tuber ended up in industrial processing water. During sugar beet processing, these quantities were 0.51 kg of 1.6 kg P ton-1 DM, and 1.04 kg of 6.56 kg N ton-1 DM sugar beet. In those cases where nutrient content in the sum of output products was higher than in the harvested crop, we lowered the nutrient content of output products by solving a system of linear equations such that the initial nutrient ratio (PDV, 2011) between output products remained unchanged. This was the case for the remaining two food processes that involved separation of harvested crop into multiple crop products, i.e. dry milling of wheat, and crushing of rapeseed. The nutrient contents of the output products of the dry milling of wheat were lowered from 2.8% to 2% N, and from 0.68% to 0.35% P. The nutrient contents of the output products from rapeseed crushing were lowered with less than 1%. To account for the relation between N and protein, we lowered the contents of intestinal digestible protein and rumen degradable protein in feed ingredients for cows with the same percentage as the percent-change in N.

Supplementary Material S7 Number of cow and pig production units (PU) (1 000 PU), land use (1 000 ha), phosphorus (P) loss through leaching and run-off (ton) and P waste through human excreta (ton) for the baseline situation, the alternative situations, and for the situation assuming higher P-surplus of 13 kg ha-1 year-1 (instead of 2.2 kg ha-1 year-1). Results presented for various percentages of protein from animals (%PA).

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| |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | |  | %PA in human diet | 0 | 10 | 15 | 20 | 25 | 60 | 65 | 80 | | Baseline | Number of cowPU | 0 | 132 | 197 | 263 | 329 | 790 | 855 | 1 053 | |  | Number of pigPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Land use | 1 147 | 884 | 895 | 899 | 916 | 1 272 | 1 351 | 1 662 | |  | P loss through leaching and run-off | 2 500 | 1 927 | 1 952 | 1 959 | 1 998 | 2 773 | 2 945 | 3 622 | |  | P waste through human excreta | 7 108 | 7 570 | 7 622 | 7 675 | 7 728 | 8 509 | 8 639 | 9 028 | |  |  |  |  |  |  |  |  |  |  | | P\_Waste\_Crop\_Animal | Number of cowPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Number of pigPU | 0 | 648 | 972 | 1 296 | 1 620 | 3 888 | 4 211 | 6 162 | |  | Land use | 869 | 847 | 830 | 813 | 823 | 1 493 | 1 611 | 1 618 | |  | P loss through leaching and run-off | 1 894 | 1 847 | 1 810 | 1 773 | 1 794 | 3 255 | 3 512 | 3 526 | |  | P waste through human excreta | 6 894 | 6 506 | 6 329 | 6 152 | 6 000 | 4 776 | 4 594 | 5 108 | |  |  |  |  |  |  |  |  |  |  | | R\_Waste\_Crop | Number of cowPU | 0 | 132 | 197 | 263 | 329 | 790 | 855 | 1 053 | |  | Number of pigPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Land use | 1 147 | 1 131 | 1 124 | 1 099 | 1 048 | 1 242 | 1 336 | 1 620 | |  | P loss through leaching and run-off | 2 500 | 2 466 | 2 450 | 2 396 | 2 284 | 2 707 | 2 912 | 3 531 | |  | P waste through human excreta | 7 108 | 7 241 | 7 307 | 7 397 | 7 531 | 8 509 | 8 639 | 9 028 | |  |  |  |  |  |  |  |  |  |  | | R\_Waste\_Animal | Number of cowPU | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 550 | |  | Number of pigPU | 0 | 804 | 1 206 | 1 608 | 2 010 | 5 177 | 5 318 | 4 216 | |  | Land use | 1 147 | 1 092 | 1 062 | 1 043 | 1 119 | 1 618 | 1 619 | 1 688 | |  | P loss through leaching and run-off | 2 500 | 2 382 | 2 315 | 2 273 | 2 438 | 3 526 | 3 529 | 3 679 | |  | P waste through human excreta | 7 108 | 6 695 | 6 493 | 6 279 | 5 982 | 5 126 | 5 582 | 7 367 | |  |  |  |  |  |  |  |  |  |  | | R\_Humexc\_ProcWater | Number of cowPU | 0 | 132 | 198 | 267 | 342 | 790 | 855 | 1 100 | |  | Number of pigPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Land use | 847 | 772 | 789 | 803 | 845 | 1 219 | 1 286 | 1 499 | |  | P loss through leaching and run-off | 1 847 | 1 683 | 1 721 | 1 750 | 1 842 | 2 657 | 2 803 | 3 269 | |  | P waste through human excreta | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  |  |  |  |  |  |  |  |  |  | | Combi\_1 | Number of cowPU | 0 | 119 | 179 | 250 | 322 | 909 | 1 017 | 1 419 | |  | Number of pigPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Land use | 498 | 465 | 486 | 508 | 532 | 809 | 865 | 1 066 | |  | P loss through leaching and run-off | 1 087 | 1 014 | 1 059 | 1 107 | 1 160 | 1 763 | 1 885 | 2 324 | |  | P waste through human excreta | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  |  |  |  |  |  |  |  |  |  | | Combi\_2 | Number of cowPU | 0 | 133 | 206 | 275 | 289 | 1 067 | 1 223 | 1 496 | |  | Number of pigPU | 0 | 0 | 0 | 51 | 495 | 0 | 0 | 0 | |  | Land use | 740 | 680 | 661 | 656 | 662 | 908 | 972 | 1 216 | |  | P loss through leaching and run-off | 1 614 | 1 483 | 1 442 | 1 431 | 1 444 | 1 980 | 2 118 | 2 651 | |  | P waste through human excreta | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  |  |  |  |  |  |  |  |  |  | | Higher P surplus | Number of cowPU | 0 | 132 | 197 | 263 | 329 | 790 | 863 | 1 108 | |  | Number of pigPU | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |  | Land use | 740 | 688 | 702 | 726 | 756 | 1 174 | 1 237 | 1 493 | |  | P loss through leaching and run-off | 9 624 | 8 944 | 9 126 | 9 439 | 9 825 | 15 262 | 16 084 | 19 408 | |  | P waste through human excreta | 7 924 | 7 999 | 7 793 | 7 769 | 7 818 | 8 761 | 8 987 | 9 653 | |

Supplementary Material S8 The effect of assuming higher phosphorus surplus (13 kg ha-1 year-1)

MacDonald *et al.* (2011) reported that top quartile fields with surpluses globally had P surpluses of more than 13 kg P ha-1­­ year-1­­. We explored the effect of assuming P surpluses or P accumulation of 13 kg P ha-1­­ year-1­­ while all other parameters were equal to that in the baseline situation (Figure S1). In this situation, mineral P input varied roughly between 21 000 ton (at 10% PA) and 35 000 ton (at 80% PA). The absolute difference in mineral P input between our baseline situation (P loss through leaching and run-off is 2.2 kg ha-1 year-1) and the situation with 13 kg P loss ha-1 year-1 through leaching and run-off or equivalent enhanced accumulation of P in soils, varies roughly between 8 400 and 18 000 ton P (i.e. 67 to 105% more mineral P input requirement in the situation with higher P surplus). In P-saturated soils, an important strategy therefore would be to lower P surplus. If P surplus is not lowered, mineral P input was minimised by minimising land use (Supplementary Material S7). The P use efficiency (P consumed by humans (Supplementary Material S7) over mineral P input) in the situation with higher P surplus ranged between 27% (at 80% PA) and 38% (at 15% PA).

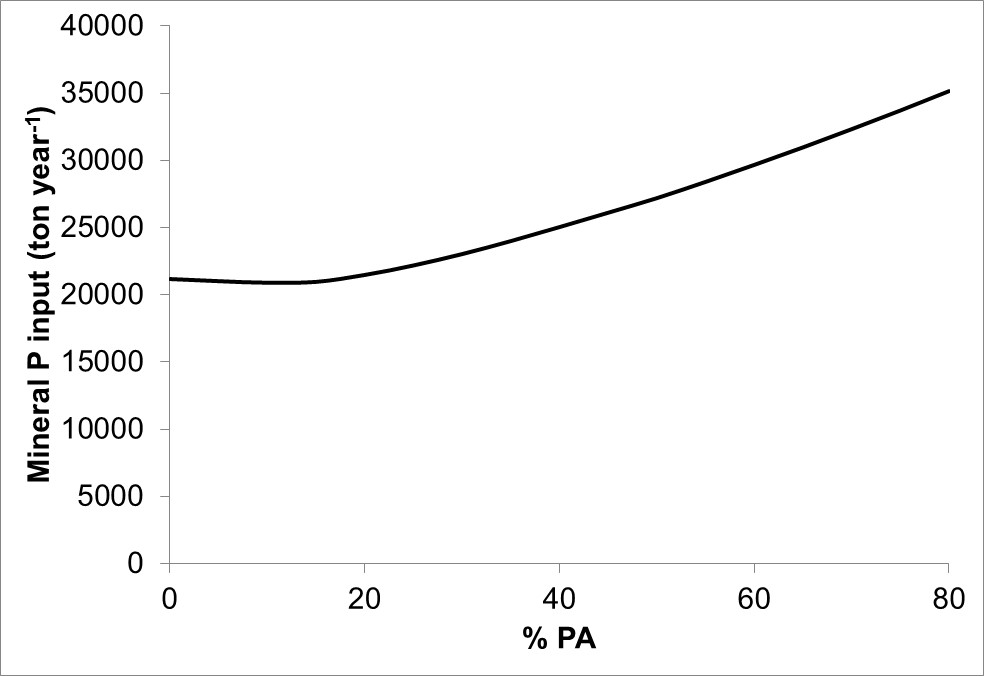


Figure S1. Mineral phosphorus (P) input (ton year-1) in relation to percentage of protein from animals (% PA) assuming P surpluses of 13 kg P ha-1­­ year-1­­ while all other parameters are equal to that in the baseline situation.

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