A Circular Economy for Phosphorus in Sweden—Is it Possible?

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Supporting Information

The MFA that underpins this paper was conducted as a prestudy to this study:

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Analysis and calculations were performed in Microsoft Excel. Here, we summarize important aspects relating to uncertainty and how we calculated the magnitude of flows, as well as phosphorus contents and efficiencies of on-site wastewater treatment.

Section A. Uncertainty Quantification

In this section, the method for quantifying uncertainties is detailed. Uncertainties were estimated using the framework developed by Hedbrant & Sörme [1]. This entails classifying sources based on their type and general reliability, which yields an uncertainty factor for the flow. This is the framework that Danius [2] recommends for handling uncertainties in MFAs, and it was for example used by [3] in a P balance of Austria. The idea is that the uncertainty of a flow can be described by a factor. Then, the interval that likely holds the true value of the flow can be calculated through both multiplying and dividing the flow with its respective uncertainty factor. The specific uncertainty factors used were taken from [3], see Table 1. Examples in Table 1 refer to the study described in the present paper. Final uncertainty factors can sometimes be a combination of several uncertainty factors. This is described further in the original article by Hedbrant & Sörme [1]. It should be noted that uncertainty factors are not necessarily sufficient to describe uncertainties in the study as a whole, since they can only describe data that have been found and quantified.

Table 1. Uncertainty factors with examples.

Uncertainty level	Uncertainty factor	Source	Example
0	1	General value from literature	Molecular weights
1	1.11	Official statistics, appropriate scientific literature	Up-to-date statistics from Statistics Sweden
2	1.33	Inofficial statistics, presentations	Share of vegetable/animal waste in food waste
3	2	Publications without literature source, educated guesses	Amount of P imported in animal feed

Section B. P-containing flows

In this section, all flows presented in the main article are listed along with their corresponding sources and uncertainty factors.

Table 2. Flows within the agriculture and food production system.

Flow	**Source**	**Calculation**	**Size (ton P/year)**	**Uncertainty factor**
Animal manure used as fertilizer on agricultural lands	Number of animals [4] and excretion values [5]	(Number of animals * P excretion values) – (P in manure to digestion facilities)	17588	1.33
Mineral fertilizer import	As reported by [6]	-	14400	1.11
Recycled digestates	Calculations based on digestion feedstock statistics [7], ratio of vegetable and animal food waste and P contents of food [8]. Digested animal by-products and manure from [9]	(Digestion feedstock material * P contents)	3770	1.47
Recycled wastewater sludge	As reported by [10]	-	1500	1.11
Lime mud from forest industry to crop production	Personal communication with [11]	-	264	1.33
Crops to animal-food-, and energy production	Harvest statistics, including silage and hay harvests [12] and P contents from the appendix section	(Harvested crops * P content)	35181	1.35
Imported feed to animal production	Feed contents [12], P contents from the appendix section	(Feed contents * P contents)	6915	2
Imported food products	Import statistics [12], P contents from the appendix section	(Imported food products * P contents)	6214	1.35
Exported food products	Export statistics [12], P contents from the appendix section	(Exported food products * P contents)	8532	1.35

Table 3. Flows within the forestry system.

Flow	Source	Calculation	Size (ton P/year)	Uncertainty factor
Wood from forestry to forest industry	Wood to forest industry [13], share of imported wood from [14]	Wood to forest industry * (1 – share of imported wood)	4697	1.47
Wood from forestry to energy sector	As reported by [13]	-	3200	1.33
Ashes returned to forestry	As reported by [15]	-	800	1.33
Atmospheric deposition	Average rates of deposition reported by [16] and [17]	Average rate of deposition * Forest area	700-6500	10
Rock weathering	Average rate of weathering reported by [18]	Average rate of weathering * Forest area	2500	2

Table 4. Flows lost to the aquatic environment.

Flow	Source	Calculation	Size (ton P/year)	Uncertainty factor
Emissions from farmland	As reported by [19]	-	1750	1.33
Emissions from fish farms	As reported by [19]	-	67	1.33
Emissions from forest land	As reported by [19]	-	1190	1.33
Emissions from wastewater treatment within the forest industry	As reported by [13]	-	270	1.33
P to aquatic environment from municipal WWTPs	As reported by [20]	-	237	1.11
P to ground filters from on-sites	Technology shares and their efficiencies [21]	Technology share * Technology efficiency	385	1.47

Table 5. Flows lost to landfill or equivalent.

Flow	Source	Calculation	Size (ton P/year)	Uncertainty factor
Ashes from forest industry to landfill	As reported by [13]	-	2100	1.33
Bio-sludge from wastewater treatment to landfill	As reported by [13], corrected for after personal communication with [22]	-	974	1.33
Lime mud from forest industry to landfill	As reported by [13]	-	302	1.33
Green liquor dregs from forest industry to landfill	As reported by [13]	-	325	1.33
Ashes from solid waste treatment to landfill	Calculations based on share of food waste, paper waste and wood waste being incinerated [7] together with P contents of paper, wood [13] and food waste [8]	(Different types of waste * corresponding P content)	1171	1.47
Compost from solid waste treatment	Calculated using feedstock data from [7], P contents of vegetable food waste from [8] and manure from [23]	(Different types of waste * corresponding P content)	313	1.47
Sludge to landfill or equivalent	Solved for using data for WWTP in- and outflows from [20] and data on current sludge recirculation from [10]	(P entering WWTPs – P in WWTP outflow – P in sludge currently recirculated)	3809	1.11
Mining waste	Personal communication with [24]	-	60000	1.33
Slag from steel industry to landfill	Solved for using feedstock data to the steel industry from [16], steel production data from [25] and P content of steel from [26]	(P input to steel production – Steel production * P content of steel)	1451	1.28
Ashes from wood in the energy sector to landfill	Solved for using data on total amount in ashes from [13] and current recirculation from [15]	(Total amount in ashes – Amount currently recirculated)	2400	1.33
Ashes from Biomal to landfill	Personal communication with [27]	-	450	1.33

Section C. P contents

In this section, the P contents of different goods are presented. For harvests of different crops, data from Statistics Sweden's yearly compilation of statistics in agriculture [4] were coupled with phosphorus contents derived from Swedish Board of Agriculture [5], the Potash Development Association [28] and the Swedish National Food Agency database [29].

Table 6. P contents of different crops (continued on next page).

Type	P content (kg P/ton)	Source
Winter wheat	3.17	[5]
Spring wheat	3.17	[5]
Rye	3.4	[5]
Winter barley	3.4	[5]
Spring barley	3.4	[5]
Oats	3.4	[5]
Winter triticale	3.4	[5]
Spring triticale	3.4	[5]
Mixed cereals	3.4	[5]
Maize	0.61	[28]
Peas	3.71	[5]
Broad beans	4.8	[28]
Winter rapeseed	6	[5]
Spring rapeseed	6	[5]
Winter turnip rape	6	[5]
Spring turnip rape	6	[5]
Flax	6	[5]
Silage	2.33 (per ton TS)	[5]
Food potatoes	0.5	[5]
Starch potatoes	0.5	[5]
Sugar beets	0.4	[5]
Cauliflower	0.6	[29]
Broccoli	0.6	[29]
Brussel sprouts	0.6	[29]
Dill	1.2 (taken for celery, which is in the same family as dill)	[29]
Fennel bulbs	0.4 (taken for carrot, which is in the same family as fennel)	[29]
Kale	0.7	[29]
Cucumbers	0.2	[29]
Iceberg lettuce	0.5	[29]
Other lettuce	0.5	[29]
Jerusalem artichokes	0.4 (taken for carrot)	[29]
Swedes	0.4	[29]
Maize	0.4 (taken for beans)	[29]
Onions	0.5	[29]
Carrots	0.4	[29]

Table 6. P contents of different crops (continued from previous page).

Type	P content (kg P/ton)	Source
Parsnips	0.4 (taken for carrot)	[29]
Parsley	0.4 (taken for carrot, which belongs to the same family as parsley)	[29]
Pumpkins	0.2 (taken for cucumber, which belongs to the same family as pumpkins)	[29]
Leeks	0.6	[29]
Rhubarb	0.6	[29]
Beetroots	0.5	[29]
Other beets	0.5 (taken for beetroot, which belongs to the beet family)	[29]
Red cabbage	0.6 (taken as average of white cabbage and kale)	[29]
Celery	1.2	[29]
Esparagus	0.4 (taken for onions)	[29]
Spinach	0.6	[29]
Pointed white cabbage	0.6 (taken as average of white cabbage and kale)	[29]
Zucchini	0.2 (taken for cucumber)	[29]
White cabbage	0.5	[29]
Garlic	0.4 (taken for onions)	[29]
Other cabbage	0.6 (taken as average of white cabbage and kale)	[29]
Other vegetables	0.52 (taken as average of other vegetables)	[29]
Cherries	0.22	[29]
Plums	0.14	[29]
Pears	0.01	[29]
Apples	0.07	[29]
Blueberries	0.2	[29]
Raspberries	0.03	[29]
Seaberries	0.12	[29]
Strawberries	0.2	[29]
Rose hip	0.11 (taken as average of other types of berries)	[29]
Blackcurrants	0.07	[29]
Grapes	0.01	[29]
Other berries	0.11 (taken as average of other types of berries)	[29]
Aubergine	0.02	[29]
Chili	0.05	[29]
Sprouts	0.07	[29]
Tomatoes	0.23	[29]
Melons	0.00	[29]
Paprika	0.15	[29]

Table 7. P contents of other food items (continued on next page).

Type	P content (kg P/ton)	Source
Beef	1.9	[29]
Pork	1.78	[29]
Lamb	1.93	[29]

Table 7. P contents of other food items (continued from previous page and continued on next page).

Type	P content (kg P/ton)	Source
Poultry	1.79 (taken for chicken with skin on)	[29]
Wild game	1.85 (taken for ground moose meat)	[29]
Processed meat	1.38 (taken as average of hot dogs and ham)	[29]
Milk, cream, yoghurt products	4.6 (taken as average of yoghurt and milk powder)	[29]
Butter	0.03	[29]
Ice cream	0.86	[29]
Cheese	0.44 (taken for 28% fat hard cheese)	[29]
Eggs	1.8	[29]
Fish, crustaceans	2.22	[29]
Processed fish products	0.12 (taken for fish balls)	[29]
Cereals	3.4	[5]
Flour, grains, malt	1.11 (taken for wheat flour)	[29]
Rice	0.13	[29]
Baked goods	0.77 (taken for bread)	[29]
Fresh vegetables	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	[29]
F0rozen vegetables	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	[29]
Dried vegetables, roots, tubers	0.5 (taken for potatoes)	[29]
Processed potato products	0.5 (taken for potatoes)	[29]
Other processed vegetable products	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	[29]
Fresh fruits, berries, nuts	0.11 (taken as average of blueberries, raspberries, seaberries, strawberries, blackcurrants and grapes)	[29]
Frozen fruits, berries	0.11 (taken as average of blueberries, raspberries, seaberries, strawberries, blackcurrants and grapes)	[29]
Syrup, jam, marmalade	0.01 (taken as average of raspberry jam and raspberry syrup)	[29]
Other processed fruits and berries	0.01 (taken as average of raspberry jam and raspberry syrup)	[29]
Sugar, molasses, honey	0 (taken for sugar)	[29]
Candy	0 (taken for jelly candy)	[29]
Coffee	3.5 (taken for instant coffee powder)	[29]
Chocolate, cacao products	1.73 (taken for dark chocolate, 70% cacao)	[29]
Tea, spices	0.55 (taken as average of tea powder and cacao powder	[29]
Soups, sauces, stocks	2.125 (taken for powdered bearnaise sauce)	[29]
Margarine, other fats	0	[29]
Other processed cereal products	0.77 (taken for bread)	[29]
"Other food items"	0.66 (taken as average of other food items)	-

Table 7. P contents of other food items (continued from previous page).

Type	P content (kg P/ton)	Source
Hard liquor	0	[29]
Wine	0.02 (taken as average of 14% red and 14% white wine)	[29]
Other alcoholic beverages	0.02 (taken for beer)	[29]
Alcohol free beverages	0.01 (taken for soda)	[29]
Tobacco	0 (data not found)	[29]
Oily seeds, fruits	2.55 (taken as average of hazelnuts, peanuts, sunflower seeds)	[29]
Oils, fats	0 (taken as average of olive oil, rapeseed oil)	[29]

Table 8. P contents of compound fodder ingredients.

Type	P content (kg P/ton)	Source
Cereal products and by-products	3.4	[5]
Oily seeds and fruits	11 (taken as extruded rapeseed)	[29]
Seeds of legumes, products and by-products	3.65 (taken as average of broad beans and peas)	[29]
Roots, tubers, products and by-products	0.25 (taken as average of sugar beet molasses and potatoes)	[29]
Other seeds and fruits, products and by-products	2.55 (taken as average of sunflower seed, hazelnuts, peanuts)	[29]
Silage	2.33	[5]
Other plants, products and by-products	0.1 (taken as average of aubergine, chili, sprouts, cucumbers, tomato, melon and paprika)	[29]
Milk products	11.3 (taken for powdered whey)	[29]
Animal products from terrestrial animals	1.7 (taken as average of pig bloodmeal, cow bloodmeal, and eggs)	[29]
Fish and other marine animals, products and by-products	2.22 (taken as average of salmon and cod fillets)	[29]
Minerals	200 (taken as monocalcium phosphate)	[22]
"Various products"	14 (taken for yeast)	[29]
"Other products"	4.78 (taken as average of other products)	-

Section D. Efficiencies of different on-site wastewater treatment technologies

In this section, the efficiencies of different on-site wastewater treatment technologies with respect to P and aquatic emissions are presented. Data were obtained from [21]. The weighted on-site efficiency becomes 0.524.

Table 9. On-site technology shares and efficiencies.

Type	Share of total	Efficiency
Latrine	0.05	0.9
1-/2-chamber tank	0.06	0.15
3-chamber tank	0.12	0.15
Closed tank	0.17	0.95
Sludge separation with infiltration bed	0.55	0.45
Urine separation	0.03	0.9
Compact treatment system	0.02	0.8

Section E. References

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