Article title: A multi-regional soil phosphorus balance for exploring secondary fertilizer potential – the case of Norway

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Online Resource 1: Appendix

Contents

1 Method for estimating P in manure, housed and from grazing

A detailed description of the procedure behind the equations for the two manure flows in Table 2 is provided here. The major animal husbandry groups of cattle, pigs and poultry were further subdivided as follows: cattle (dairy cows, suckler cows, other cattle), pigs (breeder pigs, fattening pigs) and poultry (laying hens, meat chickens). The number of animals per county was found in Statistics Norway (2014a), but for goats only the number of dairy goats was given on a county level. To get the total number of goats the number of dairy goats was divided by the share of dairy goats to the total number of goats on the national level for each year (see Online Resource 2), applying the same share for all counties as a rough approximation. The amount of P excreted per year for the different animals can be found in Online Resource 2.

The grazing cattle were dairy and suckler cows in addition to heifers, the grazing representatives of "other cattle", since bull calves are mainly kept housed. The numbers of grazing animals[1], also sheep, were found in statistics at the Norwegian Agriculture Agency (2014), but dairy and suckler cows were merged in one number. To split the number we assumed that the proportion of dairy cows to suckler cows was the same for grazing as for

[1] In the statistics of Norwegian Agriculture Agency «other cattle" are called "young cattle" ("ungdyr av storfe" in Norwegian).

the total number of dairy and suckler cows for a county. The same proportion was applied to grazing on uncultivated land.

Time spent grazing on agricultural land for dairy cows, suckler cows and sheep in each county is shown in Table A1, where numbers for 2010 are applied to all years 2009-2011. The national average grazing time on agricultural land of 17 weeks for other cattle (heifers) in 2010 was used for all counties (Statistics Norway 2014b). Numbers of grazing dairy and suckler cows on uncultivated land was also found through Norwegian Agriculture Agency (2014), and time spent grazing in the wilderness was set to 5 weeks, which is the minimum in order to receive the subsidies applied for. Grazing on uncultivated land for sheep and goats was already adjusted for in the excretion parameters (Online Resource 2) and did therefore not require further estimation.

Table A1 Number of weeks grazing on agricultural land, 2010 (Bjørlo, personal communication)

County	Dairy cows	Suckler cows	Sheep
Østfold	15.8	19.0	21.9
Akershus/Oslo	16.5	17.0	14.0
Hedmark	13.5	16.7	14.7
Oppland	13.4	16.6	14.3
Buskerud	12.2	15.8	14.8
Vestfold	19.5	18.5	21.8
Telemark	18.2	16.7	14.5
Aust-Agder	18.0	19.2	16.9
Vest-Agder	16.3	18.0	19.4
Rogaland	17.6	22.9	28.6
Hordaland	12.3	19.6	22.3
Sogn og Fjordane	11.2	16.9	16.0
Møre og Romsdal	12.5	20.3	19.2
Sør-Trøndelag	14.2	16.8	16.6
Nord-Trøndelag	14.2	19.2	19.7
Nordland	12.8	15.2	17.4
Troms	12.5	12.2	11.3
Finnmark	12.8	13.2	12.1

2 Method for estimating plant-available P in sludge

The method described here is based on statistics for wastewater treatment and literature on the plant availability of P in sewage sludge, given as mineral fertilizer equivalent (MFE), from the different types of treatment processes common in Norway (Table A2). MFE is obtained by comparing the plant uptake of P in sewage sludge and P in MF, with the same total amount of P applied to soil in each (Eq. 1).

$$MFE\ (\%) = \left(\frac{Plant\ P\ uptake\ sewage\ sludge - Plant\ P\ uptake\ control}{Plant\ P\ uptake\ MF - Plant\ P\ uptake\ control}\right) \times 100\% \qquad \text{(Eq. 1)}$$

To translate MFE into amounts of P, we considered the fertilizer effect only for the first year of application. Sewage sludge with a MFE of for example 30% means that 30% of the total amount P in the sewage sludge can replace MF.

Counties differ in their use of treatment processes in wastewater treatment plants (WWTP). The P treatment effect (percentage of P in wastewater retained in sludge after treatment) and plant availability of the retained P are both highly dependent on the choice of treatment process in WWTPs, a choice which in particular is influenced by the sensitivity of the water recipients to the discharged treated wastewater. The counties with drainage to the sensitive coastal zone between the border to Sweden in the south-east and the southernmost tip of Norway, Lindesnes, must comply with stricter demands for retention of P in sewage sludge than other counties. This makes the prevalent process technologies, and therefore the average P retention and sludge P plant availability, for these two groups of counties significantly different. In 2011, the average P treatment effect was 91% for the first group, called the North Sea counties (counties 1-10 in Fig. 1 in the article), and 37% for the other counties (Berge and Mellem 2012). Chemical and chemical-biological treatment dominated in the North Sea counties, whereas chemical, mechanical and direct discharge dominated in the other counties. We calculated the weighted average share of plant-available P in the total amount of P retained in sewage sludge for each of the two groups of counties and used this to find the amount of plant-available sludge P in each county.

Table A2 P treatment effect and mineral fertilizer equivalent (MFE) of P in sludge for different wastewater treatment methods

Treatment method	P treatment effect in wastewater (%) [1]	MFE, sludge (%)
Chemical (C)	90	15-35 (average: 25) [2]
Biological (B)	30	100 [3]
Chemical-biological (CB)	95	15-35 (average: 25) [2]
Mechanical (M)	15	100 [4]
Direct discharge (D)	0	Not applicable

[1] (Berge and Mellem 2012); [2] (Øgaard 2013); [3] (Krogstad et al. 2005); [4] Own assumption

Data on P in wastewater treatment are based on the statistical publications of Berge and Mellem (2010; 2011; 2012), which present the amount of P discharged from wastewater treatment for each of the five treatment methods in each county for the years 2009, 2010 and 2011. To simplify the estimation we used the two county groups – the North Sea counties and the other counties – to estimate the share of plant-available P of the total amount of P in sludge. The procedure is exemplified by the North Sea counties in 2011, with the discharge data and average treatment effect given in Table A3.

1. Calculation of the total amount of P in sludge produced in the county group, P_Tot (in tonnes P), as in Eq. 2

$$P\_Tot = \frac{Total\ P\ discharge}{1 - Average\ treatment\ effect} - Total\ P\ discharge = 1387\ tonnes\ P \qquad \text{(Eq. 2)}$$

where $\frac{Total\ P\ discharge}{1 - Average\ treatment\ effect} = Total\ amount\ of\ P\ in\ wastewater$

2. Estimation of the total amount of P in sludge produced by each of the treatment methods as in Eq. 3

$$P\ in\ sludge_i = \frac{Discharge_i}{1 - \left(\frac{Treatment\ effect_i}{100}\right)} - Discharge_i \qquad \text{(Eq. 3)}$$

where P in sludge$_i$ is the amount of P in sludge from treatment method i; i = C, B, CB, M, D
Discharge$_i$ is the amount of P discharged from treatment method i from Table A3
Treatment effect$_i$ is the treatment effect of treatment method i from Table A2.

Table A3 Total discharge of P (tonnes P), amount of discharged P by treatment method (tonnes P) and average treatment effect (%) for the North sea counties in 2011; estimated amounts of P in sludge by treatment method and in total (tonnes P); and share of P in sludge per treatment method of the total P in sludge

	Treatment method					Total	Average treatment effect
	Chemical	Biological	Chemical-biological	Mechanical	Direct discharge		
P discharge [1]	58.4	2.8	63.0	8.7	0.1	134.2 *	91.18 %
P in sludge	526	1,2	1197	1,5	0	1726	-
Share	0,305	0,001	0,694	0,001	0	-	-

[1] (Berge and Mellem 2012)

* The discharge from "Other treatment methods" is included in this value

The results are given in Table A3, where the estimated total amount of P in sludge summed up for all treatment methods, 1726 tonnes P, is significantly higher than the total amount of P in sludge, P_Tot, calculated in step 1. This is most likely due to the fact that actual

treatment effects in some WWTPs are not as good as the default values in Table A2, leading to overestimation of the amount of retained P in sludge by using the default values. We therefore calculated the share of the estimated P in sludge per treatment method of the estimated total P in sludge in step 3 and used this share in step 4 to estimate the amount of plant-available P in sludge.

3. Calculation of the share of sludge P for each treatment method of the estimated total amount of sludge P, $Share_i$, as in Eq. 4 (result shown in Table A3)

$$Share_i = P\ in\ sludge_i / Estimated\ total\ P\ in\ sludge \quad \text{(Eq. 4)}$$

4. Estimation of the total amount of plant-available P for the county group, P_avail (in tonnes P), as in Eq. 5

$$P\_avail = \sum_i (P\_Tot \times Share_i \times MFE_i) = 348.5\ tonnes\ P \quad \text{(Eq. 5)}$$

where MFE_i is the mineral fertilizer equivalent (in %) in sludge from treatment method i from Table A2.

5. Estimation of the percentage of plant-available P of the total amount of P in sludge for the county group to be applied for each county, in this example for the North sea counties in 2011, as in Eq. 6

$$P\_avail/P\_Tot = 348.5/1387 = 0.251 = 25.1\% \quad \text{(Eq. 6)}$$

Table A4 shows the resulting share of plant-available P of the total amount of P in sludge for the two groups of counties and for the country as a whole.

Table A4 Share of plant-available P of the total amount of sludge P per county group for 2009-2011

	2009	2010	2011	Average 2009-2011
North Sea counties	0,251	0,251	0,251	0,251
The other counties	0,364	0,377	0,314	0,352
The country as a whole	0,276	0,281	0,265	0,274

3 Method for estimating the quantity of P in grass per county

We used national statistical data for the amount of grass harvested and grazed to calculate the quantity of P in grass per county. The national total amount of P in grass, *NP_grass*, can be calculated as in Eq. 7 with the assumptions stated in Table A5.

$$NP\_grass_i\ (tons\ P) = Total\ yield_i \times \frac{1.176\ tonnes\ DM}{1000\ FEm} \times \frac{2.6\ kg\ P}{tonne\ DM} \times \frac{tonnes}{1000\ kg} \qquad \text{(Eq. 7)}$$

where i = year 2009; 2010; 2011.

NP_grass was then distributed on each county, *P_grass*, by a key combining the share of grass area in a county of the national total grass area (area of meadow for harvest and grazing)(Statistics Norway 2014c) with a productivity factor, *Pf*, obtained by dividing the production of grass per hectare in a county by the national average production per hectare (Statistics Norway 2014d)(Eqs. 8, 9).

Table A5 Assumptions for calculating P in grass

Grass	Amount	Unit	Source
Total yield 2009	2228770	1000 FEm (feed units)	Norwegian Agricultural Economics Research Institute (2014)
Total yield 2010	2050584	1000 FEm (feed units)	Norwegian Agricultural Economics Research Institute (2014)
Total yield 2011	2108784	1000 FEm (feed units)	Norwegian Agricultural Economics Research Institute (2014)
Conversion FEm to dry matter (DM) grass	1.176	Tonnes DM/1000 FEm	Adapted from Bakken et al. (2014)
P concentration grass	2.6	Kg P/tonnes DM	Johansen et al. (2003)

$$Pf_{i,j} = \frac{Yield\ of\ grass\ per\ hectare_{i,j}}{National\ average\ yield\ of\ grass\ per\ hectare_i} \qquad \text{(Eq. 8)}$$

$$P\_grass_{i,j} = NP\_grass_i \times \frac{Grass\ area\ fodder\ \&\ grazing_{i,j}}{Total\ grass\ area\ fodder\ \&\ grazing_i} \times Pf_{i,j} \qquad \text{(Eq. 9)}$$

where i = year 2009; 2010; 2011
j = county 1, 2, … , 18.

However, when summing up P in grass for all counties for a specific year i, $\sum_j P\_grass_{i,j}$, the sum was consistently around 4.5% greater than the calculated national total, NP_grass, for all years. This was presumably because combining the share of area with a production factor overestimated the actual yield for one or several counties. We expected the overestimation to be related to the same county (or counties) in each year, but were unable to identify which one. $P\_grass_{i,j}$ was therefore finally reduced by 4.5% for all counties and years.

4 Method for adjusting required P fertilization according to P-AL levels in soil

The different classes of P-AL level in soil and regression equations for correction of P requirement (%) as described by Krogstad et al. (2008) were shown in Table 3 in the article and reproduced here as Table A6 for easy access. In addition, we added a column for mean P-AL class value in order to calculate a mean correction percentage for each class (far right-hand column). P-AL data for soils in each county for the period 2001-2011 were obtained from the soil database administered by the Norwegian Institute for Agricultural and Environmental Research (Bioforsk) (Grønlund, personal communication). The representativeness of the measurements in the database for the agricultural soils in Norway is illustrated by the number of measurements relative to the agricultural area per county (Table A7). This ranged from 0.05 measurements per hectare in Telemark to 0.62 in Østfold and Oslo/Akershus, with a national average of 0.34 measurements per hectare. The representativeness in Telemark is quite low, but for the other counties it is satisfactory. Of the total cultivated area in Norway, 95.5% of the area was used for grass (65%), cereal (30%) and oilseeds (0.5%) as an average for the period 2009-2011 (Statistics Norway 2014e). We therefore assumed that the measurements are representative for all soil used for cereal, grass and oilseed production. By sorting the measurements obtained from the soil database according to the P-AL classes in Table A6, we derived a percentage of measurements per class in each county, presented in Table A7. Hence, with the assumption that percentage of soil samples within each of the P-AL classes reflects the percentage of agricultural area within these classes, it follows that 10% of the cereal, grass and oilseed area in Østfold belongs in P-AL class A and so on.

Table A6 Classes of P-AL level and percentage correction of P requirement for grass, cereals and oilseed production (Krogstad et al. 2008)

Class	P-AL value (mg per 100g soil)	Name of class	Mean P-AL class value*	Regression equation for percentage correction (Y) of P requirement	Mean percentage correction (Y) of P requirement *
A	1-5	Low	3	Y=-25*P-AL+125	50
B	5-7	Medium/ Optimal	6	Y=0	0
C1	7-10	Moderate high	8.5	Y=-14.28*P-AL+100	-21.38
C2	10-14	High	12	Y=-14.28*P-AL+100	-71.36
D	> 14	Very high	-	Y=-100	-100

* Columns added by us

Furthermore, the mean percentage correction of P requirement for a P-AL class in Table A6 was multiplied by the respective percentage of soil within that class in Table A7 and added up for all the classes in a county according to Eq. 10. This gave a weighted average percentage correction of P requirement for each county (Correction, %), as presented in Table A7.

$$Correction_j = Y_A \times S_{A,j} + Y_B \times S_{B,j} + Y_{C1} \times S_{C1,j} + Y_{C2} \times S_{C2,j} + Y_D \times S_{D,j} = \sum_i (Y_i \times S_{i,j})$$ (Eq. 10)

where $Correction_j$ is the weighted average percentage correction of P requirement for county j

Y_i is the mean percentage correction of P requirement of P-AL class i from Table A6

$S_{i,j}$ is the share of soil in P-AL class i in county j from Table A7.

Table A7 Share of P-AL measurements in each P-AL class, number of measurements, number of measurements per hectare agricultural land, and weighted average percentage correction of P requirement for grass, cereals, green fodder and silage, and oilseeds (Correction, %)

County	P-AL class [1]					No. of measurements 2001-2011 [1]	No. of measurements 2001-2011 ha^{-1}	Correction (%)
	A	B	C1	C2	D			
Østfold	10 %	15 %	25 %	19 %	31 %	46038	0.62	-45,0
Oslo/Akershus	16 %	21 %	25 %	16 %	22 %	48595	0.62	-30,6
Hedmark	17 %	16 %	23 %	20 %	24 %	25082	0.24	-34,6
Oppland	12 %	13 %	21 %	21 %	34 %	29800	0.29	-46,8
Buskerud	14 %	18 %	24 %	18 %	26 %	20015	0.39	-37,2
Vestfold	5 %	9 %	20 %	25 %	40 %	4506	0.11	-59,8
Telemark	9 %	12 %	25 %	25 %	29 %	1312	0.05	-47,2
Aust-Agder	11 %	11 %	19 %	19 %	40 %	1466	0.13	-52,1
Vest-Agder	12 %	8 %	14 %	17 %	48 %	3608	0.19	-57,1
Rogaland	8 %	6 %	10 %	14 %	62 %	23175	0.23	-70,3
Hordaland	8 %	8 %	12 %	17 %	55 %	13358	0.32	-66,2
Sogn & Fjordane	6 %	7 %	11 %	16 %	60 %	23705	0.53	-71,0
Møre & Romsdal	8 %	8 %	15 %	20 %	48 %	31358	0.56	-61,7
Sør-Trøndelag	11 %	13 %	21 %	23 %	32 %	23165	0.31	-47,8
Nord-Trøndelag	10 %	14 %	24 %	22 %	30 %	23628	0.27	-46,3
Nordland	16 %	14 %	19 %	19 %	31 %	13105	0.23	-40,5
Troms	18 %	14 %	19 %	19 %	30 %	4711	0.19	-38,8
Finnmark	22 %	14 %	20 %	19 %	25 %	2699	0.28	-32,6
Total/average	*11 %*	*13 %*	*20 %*	*19 %*	*36 %*	*339,326*	*0.34*	*-48.1*

[1] (Grønlund, personal communication)

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