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PERSPECTIVE

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

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Abstract Phosphate rock is a non-renewable source of phosphorus (P) in mineral fertilizer and many countries need to use P fertilizer more efficiently in food production. This study explored the theoretical fertilizer potential of the P-rich bioresources animal manure and sewage sludge to supply the required P fertilizer for crops. We used Norway as a case study and employed multi-regional substance flow analysis with averaged annual data for the period 2009–2011. In a status quo soil balance for agricultural soil, all counties had a positive balance with a national average of 8.5 (range between counties of 2.7–14.7) kg P ha^{-1}. In addition, two fertilizer regimes (FR) were evaluated for the period; FR1 omitted mineral P fertilizer from the balance and assumed bioresource addition matched plant P offtake regardless of soil available P, while FR2 omitted fertilizer from the balance and adjusted bioresource inputs according to whether soil available P was above (adjusted downwards) or below (adjusted upwards) the optimum soil P level. FR1 and FR2 gave a national average P surplus of 1.2 (range −7.0 to 11.2) and 6.2 (range −2.5 to 19.0) kg P ha^{-1}, respectively. The secondary P fertilizer potential of bioresources for meeting P requirements was found to be underestimated in the short term by not taking into account the actual plant-available soil P level. Our conclusion was that the P fertilizer values of manure and sludge have the theoretical potential to meet the P fertilizer requirements of all Norwegian crops assessed in both the short-term and long-term perspective.

Keywords P plant availability · Soil P balance · P-AL · P fertilizer potential · Secondary P · SFA

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Introduction

Sound management of phosphorus (P) as an essential plant nutrient is key to maintaining or increasing crop yield (Syers et al. 2008), minimizing consumption of non-renewable phosphate rock (Cordell et al. 2009) and minimizing P losses causing eutrophication of water recipients (Smith et al. 1999). Today, food

production in many countries is highly dependent on imports of primary P in mineral P fertilizer. This dependency could be reduced if secondary P in available bioresources within a country or a region were to be used more efficiently.

Geographical segregation of animal husbandry and arable farming is a source of differences in regional soil P balances, which tend to be significantly more positive in animal-dense areas than in arable-dominated areas (Senthilkumar et al. 2012). Human settlements are often unevenly distributed and are becoming increasingly urbanized. Human excreta and wastewater are viewed globally as an important renewable and easily accessible source of recycled P, and urban centres are becoming P hotspots (Cordell et al. 2009). However, both animal manure and human excreta are bulky materials and costly to transport, and national-scale analysis of material flows may therefore overestimate the feasibility of secondary P recycling from such flows (Senthilkumar et al. 2012). Multi-regional scale studies are able to give a first impression of the geographical distribution of materials within a country and create an understanding of where P-rich bioresources are generated and where P fertilizer is needed, as described by Bateman et al. (2011) for manure in England.

Past over-application of P fertilizer has resulted in a great build-up of P, including plant-available P, in European agricultural soils (Schoumans et al. 2010; Van Dijk et al. Accepted). Application of P fertilizer to crops follows the law of diminishing returns (Syers et al. 2008). Above a certain soil P level, further application of P fertilizer has limited or no effect on yields and is therefore inefficient use of a limited resource. High P accumulation in soil is also associated with increased losses of P in runoff and erosion risking eutrophication in surface waters (Smith et al. 1999). Consequently, P-rich soil is a source of P that should be tapped into with both the resource and pollution perspective in mind. Sattari et al. (2012) showed that the projected global P fertilizer demand up to 2050 could be decreased substantially by including past build-up of soil P (residual P or legacy P) as a resource. Re-aligning the inputs of P to match crop requirements is seen as an important step towards increased P efficiency (Withers et al. 2015).

Ultimately, the use of total P content in material flows can overestimate the fertilizer value of secondary P in bioresources. For example, the use of chemical precipitation in wastewater treatment plants results in a sewage sludge in which P is mainly present in aluminium/iron-bound form with low plant availability (Frossard et al. 1994; Krogstad et al. 2005). Although other factors such as soil type and content of available P in the soil also influence the plant availability of P in sludge (Krogstad et al. 2005), quantification of the plant-available P in bioresources could give a good indication of secondary P fertilizer potential.

Thus, there are three main causes of ineffective use of secondary P: (1) Geographical segregation between where secondary P is generated and where it is needed; (2) disregard of the existing plant-available soil P; and (3) the chemical form and plant availability of secondary P affecting its fertilizer value.

The main objective of this study was to explore the theoretical secondary fertilizer potential contained within P-rich bioresources, using Norway as a case study. We hypothesized that the overall net demand for mineral P fertilizers in Norwegian agriculture is close to zero if the secondary P in existing bioresources (animal manure and sewage sludge) is utilized to its theoretical potential. To examine how that potential differed geographically across the country, we disaggregated material flows down to regional county level. The theoretical fertilizer potential in animal manure and sewage sludge was explored by quantifying plant-available P and assuming a regional soil P balance without the use of mineral P fertilizer. Moreover, we used a measure for the level of plant-available P in Norwegian agricultural soils to estimate regional P fertilizer requirements, and compared those with values obtained applying a simplified strategy of maintenance fertilization that assumes optimal soil P levels.

Materials and methods

System definition

We used substance flow analysis (SFA) (see e.g. Brunner and Rechberger 2004) to develop a multi-regional soil P balance for the 19 counties in Norway, looking at the major flows of P into and out of agricultural soil. Thus, the system boundary was set around agricultural soil in each county, including permanent pasture used for fodder production and

grazing, but excluding uncultivated land[1] used for grazing, such as forest, mountain and coastal terrain. Outdoor horticulture was not included in the study due to poor availability of regional statistical data, but the amount of P in horticultural produce (including greenhouse horticulture) has been estimated to be roughly 1 % of P in total plant yields on a national scale. Greenhouse horticulture was considered outside the system boundary of agricultural soil and with negligible P flows to agricultural soil. All input flows to agricultural soil were considered to be exogenously determined except the input flows from the wastewater treatment process. This process was included in the system in order to explore how changes in sewage sludge distribution can affect inputs to agricultural soil and the soil P balance. The counties of Oslo and Akershus are often treated as one statistical entity and thus were also treated as one entity and county (Oslo and Akershus) in this study, resulting in 18 independent systems to be quantified (Fig. 1). Each flow was independently calculated and a multi-year average was produced for the period 2009–2011 in an attempt to avoid annual variations. A visualization of the system was generated by the material flow analysis freeware STAN (Fig. 2a). Some bioresources containing P were not included in the analysis, either because of lack of regional-scale data or because their use as a fertilizer in agriculture in the study period was considered to be insignificant. Meat and bone meal (MBM) produced from slaughter waste is a P-rich commercial product sold domestically and exported abroad as both fertilizer and a feed ingredient for pet and fur animals. Around 85 % of the MBM in Norway is produced in three processing plants (Viste, personal communication), and it is consequently not generated in all counties. The relevance of MBM as a potential fertilizer in the future is entirely dependent on market developments. MBM used as fertilizer was, on average for 2009–2011, in the order of 1–2 % of the total national P input to agricultural soil according to our calculations, and the proportion has since decreased further. Therefore we opted to omit MBM as a fertilizer input in the present study.
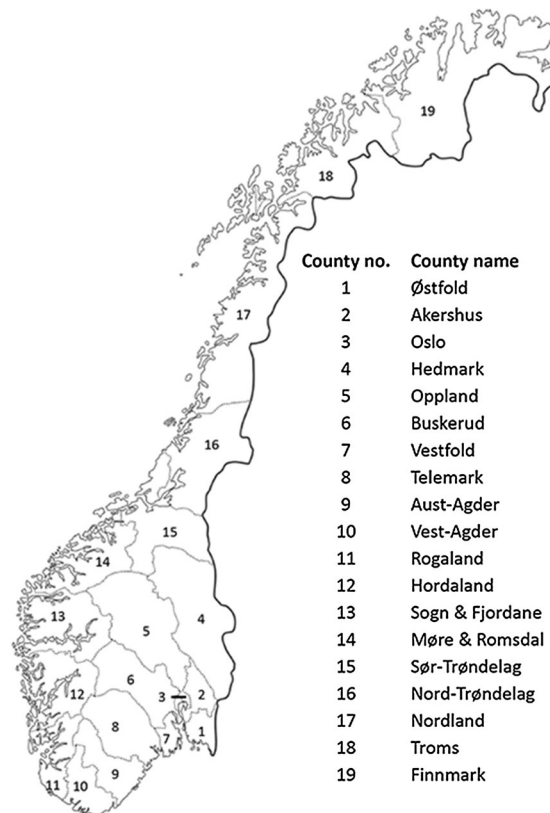

County no.	County name
1	Østfold
2	Akershus
3	Oslo
4	Hedmark
5	Oppland
6	Buskerud
7	Vestfold
8	Telemark
9	Aust-Agder
10	Vest-Agder
11	Rogaland
12	Hordaland
13	Sogn & Fjordane
14	Møre & Romsdal
15	Sør-Trøndelag
16	Nord-Trøndelag
17	Nordland
18	Troms
19	Finnmark

Fig. 1 Map showing the 19 counties in Norway. Data for counties 2 and 3 were combined in this study

Processes

Agricultural soil is defined as soil where crops are grown for human and animal consumption and that receives different materials containing P as a fertilizer or soil amendment. Agricultural soil includes permanent pastures where animals graze and deposit P-rich manure, and these areas may also be fertilized by mineral P fertilizer. Outputs of P from soil are harvested plant yields and diffuse losses through erosion and run-off. Plant residues were assumed here to be returned to soil and therefore not considered an output flow.

Wastewater treatment encompasses all treatment of collected municipal wastewater in wastewater treatment plants (WWTP) with a capacity >50 person equivalents.[2] In 2011, 83 % of the Norwegian

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[1] In Norwegian: utmarksbeite.

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[2] Statistics on wastewater treatment distinguish between WWTPs with capacity over and under 50 person equivalents
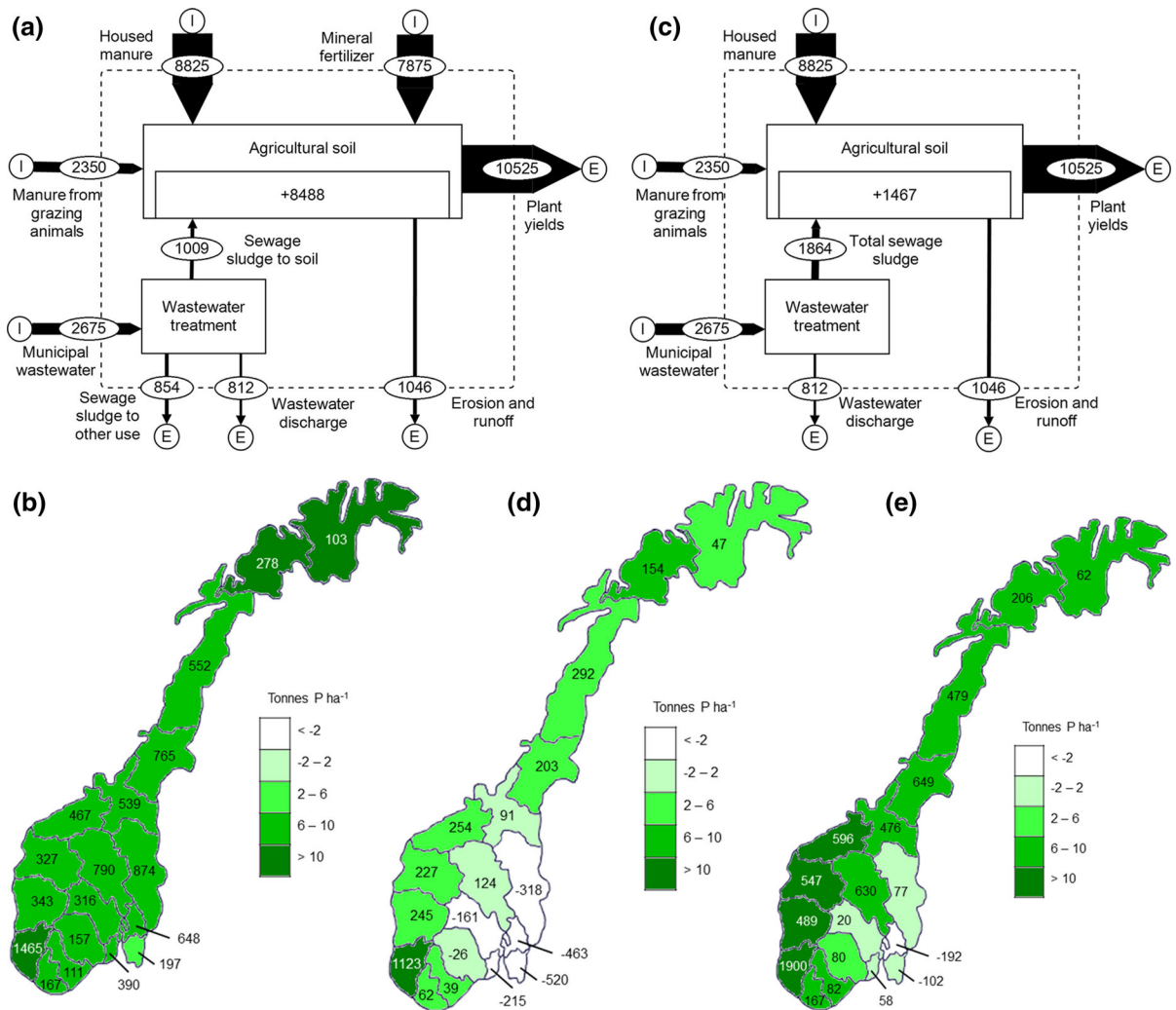
Fig. 2 a FR0: annual P balance for agricultural soil in Norway (tonnes P year^{-1}), 2009–2011. **b** FR0: annual net stock change (tonnes P year^{-1}) and net stock change per hectare (kg P ha^{-1} year^{-1}), 2009–2011. **c** FR1 and FR2: annual P balance for agricultural soil in Norway (tonnes P year^{-1}), 2009–2011.

d FR1: annual surplus fertilization (tonnes P year^{-1}) and surplus fertilization per hectare (kg P ha^{-1} year^{-1}), 2009–2011. **e** FR2: annual surplus fertilization (tonnes P year^{-1}) and surplus fertilization per hectare (kg P ha^{-1} year^{-1}), 2009–2011

population was connected to a wastewater treatment plant with a treatment capacity of more than 50 person equivalents (Berge and Mellem 2012). In addition to sewered sanitary wastewater from households and other public and private buildings, municipal

wastewater also includes wastewater from industrial processes, as well as septic tank contents emptied by tanker trucks. The treatment process produces effluent wastewater discharged to a water recipient and sewage sludge distributed for different uses. In 2011, 56 % of the sludge (measured as dry matter) was applied to agricultural land, 25 % to greening, 14 % as cover for landfill and 2 % was landfilled (Berge and Mellem 2012). Greening comprises use of sludge on urban green areas and roadside areas, for land restoration and as input in the production of soil products.

Footnote 2 continued

(pe). A pe is defined in Norway as the amount of organic matter degraded biologically over 5 days with a biochemical oxygen demand of 60 g O_2 per day (The Norwegian regulations relating to pollution control 2004).

Flows

Flow descriptions, equations and their respective data sources are shown in Tables 1 and 2. *Mineral fertilizer* (MF) is a commercial product and was quantified based on trade statistics on county level for the total sale of MF. According to our rough estimates, the amount of mineral P fertilizer not used in agriculture is approximately 5–10 % of the total amount of MF sold on national level, but breaking this down to county level would be difficult. We concluded that the regional statistics at hand provided a good enough approximation of the use of MF in agriculture. *Housed manure* from confined animals included the major animal husbandry groups: cattle, pigs, poultry, sheep and goats. We assumed that all of the housed manure was applied to agricultural soil within the county of origin and that inter-regional trade in manure was insignificant for the study period. A survey in 2000 showed that 7 % of the farms spreading manure on their land receive manure from others, while 11 % of farms sell or give away manure to others (Statistics Norway 2001). However, according to Gundersen (personal communication), most of the trade in manure is between neighbouring farms. This supports our assumption on lack of inter-regional trade. For *manure from grazing animals,* only cattle and sheep were considered for permanent pasture, depositing manure directly on the soil. The estimation of P in manure, housed and from grazing, is described in detail in the appendix (Online Resource 1). We assumed that the P in manure is as available to plants as P in MF (see for example Oenema et al. 2012; Smith and van Dijk 1987). For *sewage sludge,* we calculated the total amount of P as well as the amount of P that can replace MF, which hereafter is used interchangeably with the term plant-available P. The method used for estimating plant-available P in sewage sludge is described in detail in the appendix (Online Resource 1), and was based on statistics for wastewater treatment and literature on mineral fertilizer equivalency (MFE) of P in sewage sludge from the common treatment processes in Norway (see e.g. Øgaard 2013). The method considers the influence of a specific mix of wastewater treatment methods within a county on both the amount of P retained in sludge and its plant availability. The diffuse losses of P from soils through *erosion and runoff* were calculated by Eggestad

(personal communication) based on statistics for production subsidy applications and a method described by Eggestad et al. (2001), where the loss of P is proportional to the loss of soil and determined by e.g. soil erodibility, topography and land use. The output flow of *plant yield* was based on statistics for the nine dominant crops in Norway, which together covered 98 % of all cultivated area in Norway in the period 2009–2011 (Statistics Norway 2014): wheat, barley, oats, rye and triticale, oilseeds, potato, green fodder and silage, peas and grass. To account not only for the amount of harvested grass but also the amount of grass eaten by grazing animals on agricultural land, we used a national total amount of grass and pasture yield and distributed this between counties based on grass area and a productivity factor to account for regional differences in yield per hectare. The method for estimating P in grass yield per county is further described in the appendix (Online Resource 1).

Net stock change

Net stock change (ΔS) was calculated for the process 'agricultural soil' to indicate an addition (positive ΔS) or withdrawal (negative ΔS) of net amounts of P from the stock of soil P. The net stock change, also called the soil balance, was calculated by subtracting the sum of the outputs from the sum of the inputs as shown in Eq. 1, where i and j denote the different inputs and outputs, respectively. For the process of wastewater treatment, we assumed that there was no stock accumulation over time.

$$\sum_i Input\ i - \sum_j Output\ j = \Delta S \qquad (1)$$

Fertilizer regimes

In order to test the hypothesis and explore the research questions formulated at the start of the study, we chose to examine three fertilizer regimes (FR) for the period 2009–2011 with different soil P balances and/or fertilization strategies. These FRs only describe different perspectives on the specified period and therefore must not be confused with scenarios intended to describe the future. Nevertheless, we later discuss the possible implications of the results for future fertilization strategies.

Table 1 Description of the P flows quantified at the regional scale in Norway

Flow name	Flow description
Mineral fertilizer	The quantity of P in mineral fertilizer products used for crop production
Housed manure	The quantity of P in housed animal manure from cattle, pigs, poultry, sheep and goats
Manure from grazing animals	The quantity of P in manure from grazing animals deposited directly onto agricultural soil
Municipal wastewater	The quantity of P in collected untreated municipal wastewater
Sewage sludge to soil	The total quantity of P and the quantity of plant-available P in sewage sludge applied to agricultural soil
Sewage sludge to other use	The total quantity of P and the quantity of plant-available P in sewage sludge used elsewhere than on agricultural soil
Wastewater discharge	The quantity of P in wastewater treatment plant effluents discharged to water recipients
Erosion and run-off	The quantity of P in diffuse losses from agricultural soil
Plant yields	The quantity of P in harvested wheat, barley, oats, rye and triticale, oilseeds, potato, green fodder and silage, peas and grass, including the grass grazed by animals

- FR0: Status quo soil P balance
- FR1: Soil P balance without MF, maintenance fertilization strategy
- FR2: Soil P balance without MF, transition fertilization strategy

FR0 describes the annual status quo soil P balance, based on statistics for all described input and output flows of P for agricultural soils. Annual net agricultural soil accumulation (net stock change) was quantified in terms of the total amount of P according to Eq. 1. An estimate of the amount of plant-available P in sludge was also included, to show the status quo fertilizer value of sludge applied in agriculture.

FR1 In this fertilizer regime, we wanted to see whether plant-available P in manure and sewage sludge generated in a county, i.e. the total secondary P fertilizer potential, would be sufficient alone to provide the amount of P fertilizer required according to a maintenance fertilization strategy. Mineral fertilizer was therefore omitted as an input in this regime. In a maintenance fertilization strategy the required P fertilizer input equals the amount of P removed from the soil through plant yields. This is a simplified fertilizer regime in that it implicitly assumes optimal

levels of soil P (see FR2). As an optimal soil P level is the goal in the long term, this fertilizer regime also represents the long-term equilibrium fertilization strategy. The calculated difference between the total P fertilizer potential and the fertilizer requirement was called surplus fertilization, and was calculated as shown in Eq. 2. The total theoretical fertilizer potential in sewage sludge was considered to be the plant-available P in all sewage sludge produced in a county, i.e. the combined flow of sewage sludge to soil and sewage sludge to other use. This combined flow was called *total sewage sludge*. We omitted P losses through erosion and runoff from the calculation of surplus fertilization, since such losses are usually not taken into consideration in fertilization planning in Norway. Phosphorus losses from arable land in Norway are mainly caused by erosion (Ulén et al. 2012), which means that P is lost with the soil to which it is bound and therefore does not change the concentration of plant-available P in the remaining soil. Fertilization planning is based on concentrations of plant-available P in soil. Furthermore, in the short term the P losses by erosion are expected to be low compared with the total P stock in soil.

$$Surplus\ fertilization = Housed\ manure + manure\ from\ grazing\ animals \\ + plant\ available\ P\ in\ total\ sewage\ sludge - fertilizer\ requirement \tag{2}$$

Table 2 Methods used to calculate the P flows at the regional scale

Flow name	Equation	Material quantity sources	P content sources*
Mineral fertilizer	Mineral fertilizer applied to agricultural soil × Pc	1, 2, 3	1, 2, 3
Housed manure	Number of animals × P excreted per animal—number of animals grazing on uncultivated land × time grazing × P excreted per animal—number of animals grazing on agricultural soil × time grazing × P excreted per animal	4, 5, 6; Time grazing ag. soil: 7	5
Manure from grazing animals	Number of animals grazing on agricultural soil × time grazing × P excreted per animal	4, 6; Time grazing: 7	5
Municipal wastewater	Quantity of discharged P to water/(1—treatment effect)	8, 9, 10	
Sewage sludge to soil	Total quantity of P: (Municipal wastewater—quantity discharged P to water) × fraction of sludge to agriculture	8, 9, 10; Plant avail. P: 8–12	
	Quantity of plant-available P: total quantity of P × weighted average share of plant-available P (see Online Resource 1 for method)		
Sewage sludge to other use	Total quantity of P: (Municipal wastewater—quantity discharged P to water) × (1—fraction of sludge to agriculture)	8, 9, 10; Plant avail. P: 8–12	
	Quantity of plant-available P: Total quantity of P × weighted average share of plant-available P		
Wastewater discharge	Quantity of discharged P to water	8, 9, 10	
Erosion and run-off	Eggestad, personal communication		
Plant yields	Cereal, potato, oil seed, legume, green fodder and silage yields × Pc + grass yields × Pc × area factor × productivity factor	4; Oilseeds and legumes: 13; Grass: 14, 15	16; Grass: 17

Pc = P concentration; [1,2,3] (Norwegian Food Safety Authority 2010, 2011, 2012); [4] (Statistics Norway 2014); [5] (Karlengen et al. 2012); [6] (Norwegian Agriculture Agency 2014); [7] (Bjørlo, personal communication); [8] (Berge and Mellem 2010); [9] (Berge and Mellem 2011); [10] (Berge and Mellem 2012); [11] (Øgaard 2013); [12] (Krogstad et al. 2005); [13] (Breen, personal communication), [14] (Norwegian Agricultural Economics Research Institute 2014); [15] (Bakken et al. 2014); [16] (Antikainen et al. 2005); [17] (Johansen et al. 2003)

* Parameters used for P content in animal manure and plant yields are given in Online Resource 2

FR2 was similar to FR1 except one significant difference: the amount of P fertilizer required for producing grass, cereal, green fodder and silage, and oilseeds (98.4 % of the total plant P yield) was adjusted to account for the existing level of plant-available soil P in the calculation of fertilization surplus or shortage. The adjustment was made to approach, over a series of years, the level of plant-available soil P viewed as optimal in Norwegian fertilizer planning, regarding both yield and the risk of diffuse P losses. The reference for the adjustment was maintenance fertilization, and the fertilization strategy followed during the adjustment phase is termed *transition fertilization*. For P-deficient soils, the amount of P applied in fertilizer should exceed the amount of P removed through plant harvest, while in soils with high levels of plant-available soil P the fertilizer P amount should be lower than crop P removal. At high levels of plant-available soil P, the release of P from the soil stock covers part or all of the crop's P requirement (Krogstad et al. 2008). In Norway, plant-available P in soil is estimated by P-AL (mg per 100 g soil) extracted by the ammonium-acetate-lactate method (0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75) according to Egnér et al. (1960). Table 3 shows the different classes of P-AL

Table 3 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 100 g 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

level in soil and the recommended correction of P fertilizer requirement as a percentage of maintenance fertilization amount, as described by Krogstad et al. (2008). The recommendations bear a resemblance to the system used in the UK (Tóth et al. 2014). A P-AL level of 5–7 mg/100 g soil is considered optimal (Krogstad et al. 2008) and no correction should be made to the maintenance fertilization. P-AL measurements for 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), which records P-AL data on farm level. Norwegian regulations require fertilizer plans to be based on soil analyses no older than 8 years. Hence, data from a time span of 10 years should represent the majority of Norwegian agricultural soils, assuming that all data have been submitted to the database. For each county, the P-AL data were distributed between P-AL classes. Based on this distribution and a mean percentage correction of P requirement for each class, we calculated a correction (%) of the P requirement for grass, cereals, green fodder and silage, and oilseeds in each county. A further description of the method can be found in the appendix (Online Resource 1). The correction was multiplied by the plant P yield for the respective crop to get an adjusted fertilization requirement, which was then added to the non-adjusted P requirement for the other crops (1.6 % of total plant P yield) to obtain a corrected total fertilizer requirement. The corrected total fertilizer requirement was balanced against the same inputs as in FR1 for the surplus fertilization calculation (Eq. 2). Although the fertilizer requirement was adjusted, the system flows stayed

unchanged from FR1 and the soil P balance was therefore identical to that in FR1.

Uncertainties

Plant P uptake from sewage sludge varies with the soil type to which it is applied and the type of sludge produced at a specific WWTP (Krogstad et al. 2005; Øgaard 2013). Krogstad et al. (2005) found higher plant P uptake in a clay soil compared to a moraine soil, indicating lower P sorption capacity in the clay soil. As soil type affects plant P uptake from both sewage sludge and mineral fertilizer, the effect on the relative difference in uptake reflected in the MFE can be expected to be small. Øgaard (2013) found plant P uptake to be significantly different when equal amounts of P in chemically precipitated sludge from different WWTPs were applied to soil. This variation is reflected in the MFE range given for chemically and chemical-biologically treated sludge in Online Resource 1. We believe that the MFE values used in this study are good enough approximations for plant-available P in sludge, given the prevailing treatment technologies in the study period. Any long-term release of plant-available P from sludge beyond the year of application was assumed to be detected in P-AL measurements and would subsequently affect the P fertilization requirement. The calculation of fertilization adjustment in FR2 relied on the assumption of representativeness of the recorded soil samples for a county. This was considered to be satisfactory for all counties but one, as discussed in the appendix (Online Resource 1). The use of a mean value for the different P-AL classes (Table 3) is a simplification

associated with some uncertainty, since the measurements within each class may be skewed towards the upper or the lower limit of the class in a specific county. This simplification was made in order to use the same percentage correction values for all counties. Lastly, uncertainty in the statistical data was expected to be low. The main source of data was Statistics Norway, and we used a bottom-up approach to estimate the majority of the flows.

Results

FR0

The soil P balance (Table 4) showed a positive net stock change and thus an annual surplus application of P to agricultural soil in all counties for the period 2009–2011. The net stock change varied from 2.7 kg P ha^{-1} in Østfold to 14.7 kg P ha^{-1} in Rogaland, with a national average of 8.5 kg P ha^{-1}. The national average soil P balance was very close to the 8.6 kg P ha^{-1} estimated for the EU15 countries as a whole by Ott and Rechberger (2012), but somewhat less than e.g. the 13 kg P ha^{-1} estimated for Finland (Antikainen et al. 2005). The aggregated national flows and stock changes for the system are shown in Fig. 2a and a county-wise distribution of the net stock change is visualized on a map in Fig. 2b. Rogaland stands out, with a particularly high surplus due to the high amount of animal manure P, both housed and from grazing, in combination with MF. In most counties, P in sewage sludge contributed only a small part of the total P input to agricultural soil (≤13 %), but in the populous Oslo and Akershus region the sludge contribution was 35 % of the total input.

Table 4 FR0: Soil P balance

County	Inputs					Outputs		ΔS	Area[1]	ΔS/area
	MF	HM	MGA	SS	SSp	Yield	Loss			
Østfold	749	359	32	58	15	945	57	197	73,739	2.7
Oslo/Akershus	793	223	42	559	140	898	72	648	77,795	8.3
Hedmark	1215	718	138	40	10	1203	34	874	105,306	8.3
Oppland	671	946	249	42	11	1094	25	790	102,217	7.7
Buskerud	505	234	71	35	9	494	35	316	51,621	6.1
Vestfold	563	201	30	115	29	475	43	390	41,053	9.5
Telemark	194	139	42	16	4	225	9	157	24,966	6.3
Aust-Agder	91	83	29	1	0	85	7	111	11,108	10.0
Vest-Agder	116	168	61	26	6	186	18	167	18,965	8.8
Rogaland	503	1619	569	49	17	1115	161	1465	99,945	14.7
Hordaland	203	420	172	9	3	368	92	343	41,456	8.3
Sogn and Fjordane	192	536	139	4	1	452	93	327	44,584	7.3
Møre and Romsdal	324	634	164	0	0	556	99	467	56,310	8.3
Sør-Trøndelag	503	696	175	50	18	807	78	539	74,373	7.2
Nord-Trøndelag	683	976	185	4	2	981	103	765	87,183	8.8
Nordland	351	571	177	0	0	461	86	552	57,302	9.6
Troms	157	228	55	0	0	135	28	278	25,195	11.0
Finnmark	63	72	19	0	0	46	5	103	9519	10.8
Total	7875	8825	2350	1009	265	10,525	1046	8488	1,002,635	8.5

All numbers in tonnes P per year averaged for the period 2009–2011, except area in hectares (ha) and ΔS/area given as kg P ha^{-1} year^{-1}

MF, Mineral fertilizer; HM, Housed manure; MGA, Manure from grazing animals; SS, Sewage sludge to soil; SSp, Sewage sludge to soil, plant-available P; Yield, Plant yields; Loss, Erosion and run-off; ΔS, Net stock change; Area, Total agricultural area

[1] Statistics Norway 2014

Table 5 FR1 and FR2: Soil P balance and surplus fertilization

County	FR1/FR2						ΔS	FR1			FR2			
	Inputs				Outputs			FReq	SF	SF/area	Correction	FReq_c	SF	SF/area
	HM	MGA	TSS	TSSp	Yield	Loss								
Østfold	359	32	134	34	945	57	−477	945	−520	−7.0	−45.0	528	−102	−1.4
Oslo/Akershus	223	42	675	170	898	72	−29	898	−463	−5.9	−30.6	627	−192	−2.5
Hedmark	718	138	114	29	1203	34	−267	1203	−318	−3.0	−34.6	808	77	0.7
Oppland	946	249	91	23	1094	25	167	1094	124	1.2	−46.8	588	630	6.2
Buskerud	234	71	110	28	494	35	−114	494	−161	−3.1	−37.2	313	20	0.4
Vestfold	201	30	121	30	475	43	−167	475	−215	−5.2	−59.8	203	58	1.4
Telemark	139	42	72	18	225	9	19	225	−26	−1.0	−47.2	120	80	3.2
Aust-Agder	83	29	49	12	85	7	68	85	39	3.5	−52.1	42	82	7.4
Vest-Agder	168	61	73	18	186	18	99	186	62	3.3	−57.1	80	167	8.8
Rogaland	1619	569	140	50	1115	161	1053	1115	1123	11.2	−70.3	338	1900	19.0
Hordaland	420	172	61	22	368	92	192	368	245	5.9	−66.2	125	489	11.8
Sogn and Fjordane	536	139	10	3	452	93	141	452	227	5.1	−71.0	132	547	12.3
Møre and Romsdal	634	164	34	12	556	99	177	556	254	4.5	−61.7	214	596	10.6
Sør-Trøndelag	696	175	76	27	807	78	62	807	91	1.2	−47.8	422	476	6.4
Nord-Trøndelag	976	185	65	23	981	103	142	981	203	2.3	−46.3	535	649	7.4
Nordland	571	177	15	5	461	86	216	461	292	5.1	−40.5	275	479	8.4
Troms	228	55	17	6	135	28	137	135	154	6.1	−38.8	83	206	8.2
Finnmark	72	19	6	2	46	5	46	46	47	5.0	−32.6	31	62	6.5
Total	8825	2350	1864	511	10,525	1046	1467	10,525	1161	1.2	−48.1	5462	6224	6.2

All numbers in tonnes P per year averaged for the period 2009–2011, except SF/area given as kg P ha^{-1} year^{-1} and Correction in %

MF, Mineral fertilizer; HM, Housed manure; MGA, Manure from grazing animals; TSS, Total sewage sludge, TSSp, Total sewage sludge, plant-available P; Yield, Plant yields; Loss, Erosion and runoff; ΔS, Net stock change; FReq, Fertilizer requirement; SF, Surplus fertilization; Area, Total agricultural area; Correction, Weighted average percentage correction of P requirement for grass, cereals, green fodder and silage, and oilseeds; FReq_c, Fertilizer requirement corrected for P-AL in soil

FR1

With manure and sewage sludge as the only P inputs, the regional surplus fertilization ranged from −7.0 kg P ha^{-1} in Østfold to 11.2 kg P ha^{-1} in Rogaland (Table 5), the national average being 1.2 kg P ha^{-1}. The segregation of animal husbandry and cereal farming has an obvious impact on the regional differences. The south-western and western counties of Rogaland, Hordaland and Sogn and Fjordane have animal densities of 1.0–1.7 manure

animal units (MAU)[3] ha^{-1}, while the south-eastern counties of Østfold and Oslo and Akershus, which tend to specialize in cereal production, have animal densities of 0.3–0.4 MAU ha^{-1} (Bechmann 2005). According to the surplus fertilization data for the maintenance fertilization strategy (Table 5), 12 counties had the theoretical potential to replace the P in harvested crops by plant-available P in manure and sludge, including diversion of sewage sludge from other uses to agricultural soil. The remaining six counties (Oslo and Akershus counting as one) with negative surplus fertilization would have needed to import P fertilizer to compensate for plant P removal. The aggregated national flows and net stock change

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[3] One MAU represents around 14 kg P (The Norwegian regulations relating to organic fertiliser 2003).

for the system are shown in Fig. 2c, and the county-wise distribution of the annual surplus fertilization is visualized on a map in Fig. 2d. Plant-available P in sewage sludge constituted only a minor part of the total secondary P fertilizer potential (≤12 %) in all counties except Oslo and Akershus, where sewage sludge contributed 39 % of the total potential.

FR2

When the level of plant-available soil P was taken into account, the fertilizer requirement decreased substantially in all counties (Table 5). On the national scale, the total fertilizer requirement of 5462 tonnes P in FR2 was a 48 % reduction from FR1. This reflects overall high levels of plant-available soil P in Norway, measured as P-AL. The calculation of the weighted average percentage correction of P requirement for grass, cereals, green fodder and silage, and oilseeds showed that P fertilization for these crops could have been reduced by 31–71 % relative to maintenance fertilization for the different counties in the period 2009–2011. As these crops constitute 98.4 % of total plant P yield, the overall reduction in fertilizer requirement would be in the same range. Consequently, the surplus fertilization for the period increased dramatically from FR1, ranging from -2.5 kg ha^{-1} in Oslo and Akershus to 19 kg ha^{-1} in Rogaland. The number of counties self-sufficient in P fertilizer increased from 12 in FR1 to 16 in FR2. The aggregated national flows and stock changes for the system are identical to those in Fig. 2c, while the county-wise distribution of the annual surplus fertilization is visualized on a map in Fig. 2e.

Discussion

Short-term and long-term fertilization strategy

The results strongly suggest that too much P fertilizer was applied to Norwegian agricultural soil in the period 2009–2011, particularly according to the transition fertilization strategy in FR2 compared with the maintenance fertilization in FR1. We have reason to believe that the application of P fertilizer has not changed substantially since 2009–2011. In the short and medium term, a transition fertilization strategy should therefore be followed to reduce P fertilization

in line with the recommended corrections given in Krogstad et al. (2008) and incorporated into FR2. Once the optimal P-AL level of 5–7 in agricultural soil is reached, the long-term fertilization strategy should be maintenance fertilization in the direction described in FR1. The earlier build-up of legacy soil P can contribute P to crops over several decades. Refsgaard et al. (2013) concluded that reducing soil P-AL value from 20 to 10 at an annual cereal yield of 4 tonnes per ha would in theory take 34 years. The transition period will vary between counties depending on P-AL level and crop removal assuming that the recommended fertilization corrections are otherwise followed. One of the main reasons why the recommended fertilization corrections are not followed by many farmers today may be that the actual fertilizer value of bioresources such as animal manure and sewage sludge is unknown to the farmer or disregarded (see for example Johnston and Dawson 2005; Nesme et al. 2011; Refsgaard et al. 2004) and therefore they are not used to replace mineral P fertilizer. In addition, P-free mineral fertilizer may cost more than a complete NPK fertilizer on the Norwegian market. Another important factor is the lack of regulatory and economic incentives for farmers in livestock-dense areas to transport surplus manure P over greater distances (Knutsen and Magnussen 2011). This also applies to distribution of manure between fields operated by the same farmer, as the proportion of rented land and transport distances for manure are increasing with structural changes to larger farms (Bergslid and Solemdal 2014). Fields close to manure storage facilities tend to receive more manure than fields further away.

Theory versus P redistribution feasibility

In FR1 and FR2, we assumed that all P in manure and sewage sludge generated in a county could be used within that county where P fertilizer is needed. This requires a redistribution of secondary P fertilizer between farms and between municipalities,[4] where distances may be great, meaning that this is a costly endeavour, especially for bulky animal manure (Liu et al. 2008). Redistribution of secondary P fertilizer is expected to depend on economic incentives, technology, regulatory framework, institutional ownership

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[4] The lowest political administrative level in Norway—a county is made up of municipalities.

and social acceptance of the use of secondary P fertilizer, in order for this theoretical potential to be fully explored (Cordell et al. 2009; Koppelaar and Weikard 2013). By not considering the challenges with P redistribution within and between regions in a country, the recycling potential may be overestimated (Senthilkumar et al. 2012). The feasibility of how and when such redistribution may take place was not examined in this study. Hence, the surplus fertilization indicating the amount of secondary P which may be exported from a county must be considered a theoretical quantity on an aggregated level, delineating what can be achieved. The drivers of redistribution will in effect decide how fast a county can move from its current P management practice into de facto transition fertilization. Nevertheless, the overall consequence of realizing the full theoretical potential in all counties is a national surplus of secondary P fertilizer in Norway as a whole, both during the transition fertilization phase and in the long term with maintenance fertilization (see SF totals in Table 5). This surplus could either be stored in a P 'bank' for later use or exported to other countries. The share of the surplus that could be absorbed by greening or horticulture is considered to be minor.

Expanded wastewater potential

In this study we only considered the amount of P in sewage sludge that can replace mineral fertilizer P, given existing technology for wastewater treatment. However, we expect wastewater treatment processes in the future to be able to recover and recycle a greater part of the P in the form of various wastewater-based fertilizer products. This expectation is based on an increased awareness surrounding P as a valuable resource [for example the inclusion of phosphate rock on the list of critical raw materials in the EU (European commission 2014)] and national efforts to reduce losses of P to waterways in compliance with the EU Water Framework Directive. In addition to P recovery from sewage sludge, there are options to source-separate sanitary wastewater, which would allow P-rich fractions such as urine or blackwater to be separately treated in systems designed for resource reuse (Langergraber and Muellegger 2005; Udert and Wächter 2012). The factors for P recovery and recycling from wastewater used in this study thus need to be revisited at a later date.

Relative regional importance of manure versus sludge

Given that there are limited resources among relevant actors to help increase recycling of P from bioresources regionally and nationally in the years to come, the results (see FR1) suggest that priority should be given to recycling and redistribution of P in animal manure in all counties. However, in Oslo and Akershus the combination of a greater population density and agricultural activity dominated by cereal production has made the P fertilizer potential in wastewater almost equally interesting. From this, we concluded that efforts to recycle secondary P fertilizer from bioresources should be informed by their relative regional importance. There will also be important insights to be gained from further disaggregating regional data to see how bioresources vary in relative importance on a smaller scale. Several cities outside Oslo and Akershus are experiencing increased urbanization and may become regional hotspots for secondary P from wastewater and organic household waste (Cordell et al. 2012), even though animal manure dominates the county as a whole.

Conclusions

This study explored the theoretical potential of the bioresources animal manure and sewage sludge to supply the P fertilizer requirement of crops in Norway. It was found that if P in these resources were to be well redistributed within and between counties, Norway as a whole could be self-sufficient in P fertilizer for all crops assessed in both in the short and the long term. Taking the recorded levels of plant-available soil P into account substantially decreased the amount of P fertilizer required compared with a maintenance fertilization strategy assuming optimal soil P levels. Maintenance fertilization and an optimal soil P level are the goal in the long run, but overestimate the P fertilizer requirement in Norway in the short term. Similarly, the maintenance fertilization strategy underestimates the potential of bioresources to supply the crop P fertilizer requirement in the short term in regions with high levels of plant-available soil P.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

Antikainen R, Lemola R, Nousiainen JI, Sokka L, Esala M, Huhtanen P, Rekolainen S (2005) Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. Agric Ecosyst Environ 107: 287–305

Bakken AK, Langerud A, Johansen A (2014) Fastsetting av normavlingar i eng. Bioforsk Report no. 2 vol 9. Bioforsk

Bateman A, van der Horst D, Boardman D, Kansal A, Carliell-Marquet C (2011) Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. Resour Conserv Recycl 55:1146–1153

Bechmann M (2005) The phoshporus index tool for assessing phosphorus transfer from agricultural areas in Norway. Dissertation, Norwegian university of life sciences

Berge G, Mellem KB (2010) Kommunale avløp. Ressursinnsats, utslipp, rensing og slamdisponering 2009. Gebyrer 2010. Statistics Norway, Oslo

Berge G, Mellem KB (2011) Kommunale avløp. Ressursinnsats, utslipp, rensing og slamdisponering 2010. Gebyrer 2011. Statistics Norway, Oslo

Berge G, Mellem KB (2012) Kommunale avløp. Ressursinnsats, utslipp, rensing og slamdisponering 2011. Gebyrer 2012. Statistics Norway, Oslo

Bergslid IK, Solemdal L (2014) Husdyrgjødsel og lagerkapasitet. Bioforsk TEMA Nr.1 januar 2014

Brunner PH, Rechberger H (2004) Practical handbook of material flow analysis. Lewis Publishers, CRC Press LLC, Boca Raton

Cordell D, Drangert J-O, White S (2009) The story of phosphorus: global food security and food for thought. Glob Environ Chang 19:292–305

Cordell D, Neset TSS, Prior T (2012) The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security. Curr Opin Biotechnol 23:839–845

Eggestad HO, Vagstad N, Bechmann M (2001) Losses of Nitrogen and Phosphorus from Norwegian Agriculture to

the OSPAR problem area. Jordforsk report no. 99/01. Norwegian Centre for Soil and Environmental Research

Egnér H, Riehm H, Domingo WR (1960) Untersuchungen über die chemische Boden-Analyse als Grundlage für die Beurteilung des Nährstoffzustandes der Boden. Kungliga Lantbrukshögskolans Annaler 26:199–215

European Commission (2014) Report on critical raw materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials

Frossard E, Tekeley P, Grimal JY (1994) Characterization of phosphate species in urban sewage sludges by high-resolution solid-state 31P NMR. Eur J Soil Sci 45:403–408

Johansen A, Ljøkjel K, Nordang L (2003) Grovforet åleine kan sjelden gi ei god nok mineralforsyning til drøvtyggarar. Grønn Kunnskap 7:103–111

Johnston AE, Dawson JC (2005) Phosphorus in agriculture and in relation to water quality. Agricultural Industries Confederation, Peterborough

Karlengen IJ, Svihus B, Kjos NP, Harstad OM (2012) Husdyrgjødsel; oppdatering av mengder gjødsel og utskillelse av nitrogen, fosfor og kalium. Sluttrapport. UMB

Knutsen H, Magnussen AvZ (2011) Gjødselvareforskriften er under revisjon - mulige konsekvenser for jordbruket i Rogaland. NOTAT 2011-10. NILF

Koppelaar RHEM, Weikard H-P (2013) Assessing phosphate rock depletion and phosphorus recycling options. Glob Environ Chang 23:1454–1466

Krogstad T, Sogn TA, Asdal Å, Sæbø A (2005) Influence of chemically and biologically stabilized sewage sludge on plant-available phosphorous in soil. Ecol Eng 25:51–60

Krogstad T, Øgaard AF, Kristoffersen AØ (2008) New P recommendations for grass and cereals in Norwegian agriculture, vol 4. In: Nordic Association of Agricultural Scientists (NJF) Report, pp 42–46

Langergraber G, Muellegger E (2005) Ecological sanitation—A way to solve global sanitation problems? Environ Int 31:433–444

Liu Y, Villalba G, Ayres RU, Schroder H (2008) Global phosphorus flows and environmental impacts from a consumption perspective. J Ind Ecol 12:229–247

Nesme T, Brunault S, Mollier A, Pellerin S (2011) An analysis of farmers' use of phosphorus fertiliser in industrial agriculture: a case study in the Bordeaux region (south-western France). Nutr Cycl Agroecosyst 91:99–108

Norwegian Agricultural Economics Research Institute (2014) NILF Statistics, Total annual accounts for the agriculture 1959–2014, Post 820F. www.nilf.no/statistikk/totalkalkylen/2014_1/BMgrupper/Totalkalkylen-alle_poster. Accessed 6 Aug 2014

Norwegian Agriculture Agency (2014) Data from statistics on production subsidy applications, various tables, 2009–2011. www.slf.dep.no/no/produksjon-og-marked/produksjonstilskudd/dokumentarkiv/statistikk. Accessed 26 Nov 2014

Norwegian Food Safety Authority (2010) Mineralgjødselstatistikk 2008–2009. www.mattilsynet.no/planter_og_dyrking/gjodsel_jord_og_dyrkingsmedier/mineralgjodsel_og_kalk/omsetningsstatistikk_mineralgjodsel.5266. Accessed Nov 2013

Norwegian Food Safety Authority (2011) Mineralgjødselstatistikk 2009–2010. www.mattilsynet.no/planter_og_dyrking/gjodsel_jord_og_dyrkingsmedier/mineralgjod

sel_og_kalk/omsetningsstatistikk_mineralgjodsel.5266. Accessed Jan 2014

Norwegian Food Safety Authority (2012) Mineralgjødsel-statistikk 2010–2011. www.mattilsynet.no/planter_og_dyrking/gjodsel_jord_og_dyrkingsmedier/mineralgjodsel_og_kalk/omsetningsstatistikk_mineralgjodsel.5266. Accessed Jan 2014

Oenema O, Chardon W, Ehlert PAI, Van Dijk KC, Schoumans OF, Rulkens WH (2012) Phosphorus fertilisers from by-products and wastes. In: Proceedings of 717 international fertiliser society, Leek, UK

Øgaard AF (2013) Plantetilgjengelig fosfor i avløpsslam - Testing av analysemetodikk for tilgjengelig fosfor. Bioforsk Report no.34 vol 8. Bioforsk

Ott C, Rechberger H (2012) The European phosphorus balance. Resour Conserv Recycl 60:159–172

Refsgaard K, Asdal Å, Magnussen K, Veidal A (2004) Organisk avfall og slam andvendt i jordbruket. Egenskaper, kvalitet og potensial - holdninger blant bønder. NILF-rapport 2004-5. NILF, Oslo

Refsgaard K, Bechmann M, Blankenberg A-GB, Kvakkestad V, Kristoffersen AØ, Veidal A (2013) Evaluering av tiltak mot fosfortap fra jordbruksarealer i Norge. Kost-effekt vurderinger. NILF-rapport 2013-3. NILF, Oslo

Sattari SZ, Bouwman AF, Giller KE, van Ittersum MK (2012) Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proc Natl Acad Sci 109:6348–6353. doi:10.1073/pnas.1113675109

Schoumans OF, Rulkens WH, Oenema O, Ehlert PAI (2010) Phosphorus recovery from animal manure. In: Technical opportunities and agro-economical perspectives. Alterra report 2158. Alterra, Wageningen

Senthilkumar K, Nesme T, Mollier A, Pellerin S (2012) Regional-scale phosphorus flows and budgets within France: the importance of agricultural production systems. Nutr Cycl Agroecosyst 92:145–159

Smith KA, van Dijk TA (1987) Utilisation of phosphorus and potassium from animal manures on grassland and forage crops. In: van der Meer HG, Unwin RJ, van Dijk TA, Ennik GC (eds) Animal manure on grassland and fodder crops.

Fertilizer or waste?. Martinus Nijhoff Publishers, Dordrecht, pp 87–102

Smith VH, Tilman GD, Nekola JC (1999) Eutrophication: impacts of excess nutrient inputs on freshwater, marine and terrestrial ecosystems. Environ Pollut 100:179–196

Statistics Norway (2001) Lagring og spredning av hus-dyrgjødsel. http://ssb.no/jord-skog-jakt-og-fiskeri/artikler-og-publikasjoner/mest-spredning-av-husdyrgjodsel-paa-eng–77835. Accessed 22 May 2015

Statistics Norway (2014) Data from StatBank Norway, various tables, 2009–2011. www.ssb.no/en/statistikkbanken. Accessed 12 Mar 2014

Syers JK, Johnston AE, Curtin D (2008) Efficiency of soil and fertilizer phosphorus use. Reconciling changing concepts of soil phosphorus behaviour with agronomic information. FAO Fertilizer and plant nutrition bulletin 18. Food and Agriculture Organization of the United Nations, Rome

The Norwegian regulations relating to organic fertiliser (2003) FOR-2003-07-04-951. Published in 2003, folder no. 11. https://lovdata.no/dokument/SF/forskrift/2003-07-04-951

The Norwegian regulations relating to pollution control (2004) FOR-2004-06-01-931. Published in 2004, folder no. 9. https://lovdata.no/dokument/SF/forskrift/2004-06-01-931

Tóth G, Guicharnaud R-A, Tóth B, Hermann T (2014) Phosphorus levels in croplands of the European Union with implications for P fertilizer use. Eur J Agron 55:42–52

Udert KM, Wächter M (2012) Complete nutrient recovery from source-separated urine by nitrification and distillation. Water Res 46:453–464

Ulén B, Bechmann M, Øygarden L, Kyllmar K (2012) Soil erosion in Nordic countries—future challenges and research needs. Acta Agric Scand Sect B Soil Plant Sci 62:176–184

Van Dijk KC, Lesschen JP, Oenema O (Accepted) Phosphorus flows and balances of the European Union Member States. Sci Total Environ

Withers PJA et al (2015) Stewardship to tackle global phosphorus inefficiency: the case of Europe. Ambio 44(Suppl. 2):193–206. doi:10.1007/s13280-014-0614-8