Article title: Redistributing Phosphorus in Animal Manure from a Livestock-Intensive Region to an Arable Region: Exploration of Environmental Consequences
Sustainability
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Supplementary Material

Contents

1. Lack of Incentives for Manure Nutrient Redistribution in Norway

The existing regulations in Norway do not incentivise slurry management options beyond storage and local application on-farm. Current regulations limit manure P application to soil to 35 kg P per hectare (ha) [1], which for a normal grass or cereal yield is an over application of P fertiliser in Norway given an optimal soil P level. There are no limits to the application rate of additional mineral P fertiliser.

Furthermore, the livestock dense areas in the south-western and western parts of Norway are located outside the geographical scope of Norwegian nitrate regulations and its limits on manure N application to soils [1]. Hence, transport of manure between regions occurs on a purely anecdotal scale [2], as do trials on manure separation.

2. Calculating P Fertilizer Requirement from Soil P Levels

The phosphorus (P) fertilizer requirement in the donor and recipient region was calculated based on assumptions for the levels of plant available soil P and the crop P requirement. Plant available soil P was estimated by the P-AL method in Norway according to Egnér et al. [3]. Krogstad et al. [4] described the different classes of P-AL levels in agricultural soil in Norway and how P fertilizer requirements should be corrected for P-AL levels to acknowledge the contribution to plant uptake of plant available P already in the soil (Table A1). For the donor region we assumed a very high P-AL level, the equivalent of P-AL >14 (mg per 100g soil), which leads to a reduction of 100% in the required P fertilizer. The Time catchment area, representative for the high animal density areas in the donor region, has P-AL levels well above 14 [5]. For the recipient region we assumed a moderate high P-AL level of 9 (mg per 100g soil), which according to Table A1 gives a reduction of 28.5% in the P fertilizer requirement. Thus, the P fertilizer requirement for a crop that needs 14 kg P/ha, as in the case of the recipient region in this paper, is 10 kg P/ha. The difference of 4 kg P/ha is assumed supplied from the plant available P already in the soil.

Table A1. Classes of P-AL level and percentage correction of P requirement for grass, cereals and oilseed production [4]

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

3. CH_4-C Emissions from Storage of Digested Slurry Fractions

According to Sommer et al. [6] CH_4 emissions of stored digested slurry decreased by 90% compared to non-digested slurry. We assumed the same to hold for the storage of separated fractions of digested slurry. Further, we interpreted the 90% reduction in CH_4 to include the effect of taking out carbon during digestion in the form of CH_4 and CO_2 in produced biogas. Therefore we calculated a 90% reduction in the emission of the undigested liquid fraction and converted this to a new emission factor for digested fractions (kg CH_4-C/kg OM). The calculation method is shown below with the example of liquid fraction from decanter centrifuge (DC) separation.

We first calculated the emission from undigested liquid fraction by multiplying the emission factor for undigested liquid fraction (given in Table 3 in the article text) with the amount of OM in liquid fraction of DC separation (given in Table 2 in the article text):

0.4% CH_4-C/OM * 33.9kg OM = 0.136kg CH_4-C

We then reduced this emission with 90% to get the ideal emission that we wanted to have from the digested liquid fraction:

0.136kg CH_4-C * 0.1 = 0.0136kg CH_4-C

Lastly, we divided this ideal emission by the amount of OM going into the storage of the digested liquid fraction (given in Table 2 in the article text) to obtain a new emission factor for CH_4-C based on the amount of OM to be stored:

0.0136kg CH_4-C/22.4kg OM = 0.0006kg CH_4-C/kg OM = 0.06% CH_4-C/OM

The same new emission factor was obtained for the digested liquid fraction from screw press separation, and the same procedure was followed for the digested solid fractions.

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The emission reduction corresponded to a B_0 in digested slurry of 0.035 m^3 CH_4/kg OM, as compared to 0.23 m^3 CH_4/kg OM given by Morken et al. [7]. The B_0 for digested slurry fractions was calculated in the following way:

Kg CH4-C emitted = kg OM * Eq.1 in article text = kg OM * B_0 * 0.67kg CH_4/m^3 CH_4 * (MCF/100%)/(1.34kg CH_4 /kg CH_4-C)

0.0136kg CH4-C = 22.4kg OM * B_0 * 0.67kg CH_4/m^3 CH_4 * 0.035/(1.34kg CH_4 /kg CH_4-C)

B_0 = 0.0136/(22.4 * 0.67 * 0.035/1.34) = 0.0348 ≈ 0.035m^3 CH_4/kg OM

The B_0 of 0.035 was the same for digested solid and liquid fractions after both SP and DC separation.

4. Some Background Information on FracLEACH Factors

FracLEACH is the fraction of all applied N to soil (from mineral fertilizer and manure as well as mineralization) that is lost through leaching and runoff [8]. Estimates for FracLEACH in Norway were updated by Bechmann et al. [9], where data from various catchment areas are gathered through the Agricultural Environmental monitoring program (JOVA). We used the catchment area of Time as representative for the donor region, and the FracLEACH for this catchment area (17%) was also used by Bechmann to represent intensive grass production as a general agricultural production system in Norway. For the recipient region we used the Skuterud catchment area as a representative catchment area, and the FracLEACH for Skuterud (31%) was also used by Bechmann to represent cereal production on marine sediments as a general agricultural production system in Norway. The lower FracLEACH for Time compared to Skuterud can be explained by differences in soil, crops and landscapes, as well as tillage practice. The Time catchment area has a constant grass cover that can take up N almost all year round, which reduces the fraction of N lost, while the Skuterud catchment area is subject to tillage, also in autumn, and therefore loses more N through runoff in particular.

However, FracLEACH only provides the amount of total N lost per amount of N applied (kg N/kg N), while we needed information about the amount of nitrate N lost. We found the share of nitrate N lost per total N lost from data given in Bechmann [10](p. 18). Between the 12 sites monitored, the share varied between 70 to 85% NO_3-N of the total N lost, with the average being 77%. For this study we rounded off and used a factor of 75% to calculate the amount of NO_3-N lost.

The emission factor for NO_3-N therefore consists of two elements: the FracLEACH and the percentage NO_3-N of total N lost, which are multiplied together. This gives an emission factor of kg NO_3-N per kg N applied to the field.

Emission factor NO_3-N, donor region = $FracLEACH_{Time}$ * 0.75 (kg NO_3-N/kg N)

= 0.17 *0.75 NO_3-N/kg N

= 0.128 kg NO_3-N/kg N

Emission factor NO_3-N, recipient region = $FracLEACH_{Skuterud}$ * 0.75 (kg NO_3-N/kg N)

= 0.31 *0.75 NO_3-N/kg N

= 0.233 kg NO_3-N/kg N

5. More Information on the MFE Calculation for N

The MFE for ammonium-N (MFE N_{min}) for Rogaland was calculated as a weighted average between spreading in the growing season (spring + summer) and in autumn, weighted by the share of manure spread in each season (Table 1 in the article text). Spreading in autumn reduced the MFE N_{min} by 10% due to leaching, assuming that there was still plant growth in a period after spreading [11]. A weighted average was also used to calculate mineralisation of organic N (MFE N_{org}) in Rogaland soil, but mineralisation in autumn is considered to be negligible [11]. Since all application of manure products at the recipient farm in Akershus was assumed to take place in spring, there was no need to use a weighted average for the recipient farm.

6. Selected Parameters for Perturbation Analysis

Table A2 below provides the 23 parameters used for the perturbation analysis of the reference scenario and the AD_SP scenario. The original value was increased by 10% for all parameters.

Table A2. Parameters used for the perturbation analysis

Parameter	Description	Original value	New value
Slurry characterization			
DM content manure	Amount of DM as percentage of wet weight	10.4	11.44
OM share of DM in manure	Share of OM as percentage of DM	88	96.8
Tot-N content manure	Amount of Tot-N as kg/tonne raw manure	6.2	6.82
NH4-N content manure	Amount of NH4-N as kg/tonne raw manure	3.6	3.96
P content manure	Amount of P as kg/tonne raw manure	0.72	0.79
K content slurry	Amount of K as kg/tonne slurry	3.4	3.74
Amount of manure per cow	Amount of manure produced per dairy cow as tonne/month	1.64	1.80
Amount of wash water per cow	Amount of water added to the manure during in-house storage as tonne/month and cow	1.2	1.32
OM degradation			
OM_deg_house_long	Degradation of OM, long in house storage as percentage of OM	10	11
OM_deg_house_short	Degradation of OM, short in house storage as percentage of OM	5	5.5
OM_deg_store_liq	Degradation of OM, liquid fraction, outside storage as percentage of OM	10	11
CH4 emission storage			
CH4 emission long storage manure cellar	CH4 emission from long in house storage as percentage of OM	2.0	2.2
Separation efficiencies for screw press (SP)			
Separation efficiency mass	Percentage of mass separated to solid fraction	11	12.1
Separation efficiency DM	Percentage of DM separated to solid fraction	37	40.7
Separation efficiency OM	Percentage of OM separated to solid fraction	37	40.7
Separation efficiency Tot-N	Percentage of Tot-N separated to solid fraction	15	16.5
Separation efficiency NH4-N	Percentage of NH4-N separated to solid fraction	11	12.1
Separation efficiency P	Percentage of P separated to solid fraction	17	18.7
Separation efficiency K	Percentage of K separated to solid fraction	11	12.1
NH3 field application			
NH3 emission app on grass	NH3 emission, liquid application grass, as percentage of N	29	31.9
NH3 emssion solids app on arable land	NH3 emission, solid application cereal, as percentage of N	4	4.4
NO3 field application			
NO3 emission app on grass	NO3 emission as percentage of applied N, grass	12.8	14.08
NO3 emission app on arable land	NO3 emission as percentage of applied N, arable land	23.3	25.63

DM = dry matter; OM = organic matter; “deg” = degradation, “house” = in house storage; “liq” = liquid fraction; “app” = field application

7. Under- and Over-Application of Nutrients

Table A3 below presents the under- and over-application of plant available N, P and K per scenario and for the two regions, which tells us something about how the plant nutrient requirement is met for the area used for spreading. Because the P/N ratio in cattle manure is higher than what cereal crops generally require, under- or over-application of nutrients occurs depending on the nutrient used as the basis for application. Solid-liquid separation further increased the P/N ratio in the solid fraction compared with unseparated slurry, the centrifuge more than the screw press. Any under application of a nutrient is assumed met by application of additional mineral fertilizers, but the production and application of this mineral fertilizer is considered outside the scope of the study.

The spreading area in the recipient region increased with the use of decanter centrifuge (DC). This was because the transported manure was spread according to P requirement per hectare and the DC separated more P to the transportable solid fraction than the screw press (SP). Nitrogen was under applied in all scenarios and in both the donor and recipient region, but the under application was greater in the scenarios employing DC separation compared to the two SP scenarios. The DC increased the separation of P more than the N separation, which further increased the nutrient imbalance in the transported fractions compared to the SP separation. With a greater required spreading area for the increased amount of P, the amount of N spread per hectare decreased – and so the under application increased. DC separation also increased the under application of K in the recipient region, and can be explained in the same way as for N. The over application of P and K in the donor region decreased with DC separation compared to SP, since more P and K was separated to the solid fraction while the spreading area remained the same as in the reference scenario.

Table A3. Under and over application of nutrients in the different scenarios. Over application is shown in positive numbers and under application with negative numbers.

Scenario	Spreading location	Spreading area (ha)	N over/under application (kg N)	P over/under application (kg P)	K over/under application (kg K)
Ref	Donor	0,021	-4,14	0,72	2,44
SP	Donor	0,021	-3,77	0,60	1,79
	Recipient	0,012	-1,01	0,00	0,04
DC	Donor	0,021	-3,92	0,21	1,50
	Recipient	0,051	-4,92	0,00	-1,61
AD_SP	Donor	0,021	-3,43	0,60	1,79
	Recipient	0,012	-0,96	0,00	0,04
AD_DC	Donor	0,021	-3,60	0,21	1,50
	Recipient	0,051	-4,85	0,00	-1,61
NoSep	Recipient	0,072	-4,85	0,00	2,29

8. Quantification of Contributions – the Data behind Figure 4 in the Main Text

The contribution of the different life cycle processes to environmental impact categories for the different scenarios are shown in numbers in Table A5-A9 below. Scientific notation is used for all numbers except net impacts. Examples of scientific notation: 15 = 1.50E+01; 0.36 = 3.60E-01. Some of the process were renamed in the paper, so to facilitate the study of Table A5-A9, Table A4 will present old and new names.

Table A4. Impacts of the different life cycle processes on the climate change potential for the different scenarios.

Former process name	Final process name in paper	Comment
Substitution biogas	Avoided fossil fuel	
Storage solids/liquids	End-product storage	
Application solids	Field application, recipient	
Application liquids	Field application, donor	Since the NoSep scenario involved application of liquids (slurry) the impacts were first attributed to Application liquids. However, with the final name, the impacts were moved to "Field application, recipient".
Avoided min fert	Avoided mineral fertiliser donor	The word "donor" was left out by mistake. In the paper, the avoided mineral fertiliser for the donor and recipient is presented combined in "Avoided mineral fertiliser".

Table A5. Impacts of the different life cycle processes on the climate change potential for the different scenarios.

	Global warming potential (kg CO2-equivalents)													
Scenario	In house storage	Anaerobic digestion	Upgrading	Substitution biogas	Separation	Storage solids	Storage liquids	Hygienization	Transport to recipient	Application solids	Application liquids	Avoided min fert recipient	Avoided min fert	Net impact
Ref	6.94E+01	-	-	-	-	-	-	-	-	-	3.77E+01	-	-2.30E+01	84
SP	1.43E+01	-	-	-	1.66E-01	8.78E+00	1.89E+01	3.95E-01	1.59E+01	5.71E+00	3.24E+01	-5.30E+00	-2.79E+01	63
DC	1.43E+01	-	-	-	6.49E-01	1.61E+01	9.67E+00	5.00E-01	2.01E+01	1.04E+01	2.76E+01	-1.05E+01	-2.63E+01	63
AD_SP	1.43E+01	4.41E+00	5.36E+00	-2.87E+01	1.63E-01	7.56E+00	1.14E+01	3.88E-01	1.56E+01	3.32E+00	1.91E+01	-6.03E+00	-3.32E+01	14
AD_DC	1.43E+01	4.41E+00	5.36E+00	-2.87E+01	6.39E-01	1.40E+01	9.51E+00	4.93E-01	1.99E+01	6.41E+00	1.75E+01	-1.16E+01	-3.09E+01	21
NoSep	6.94E+01	-	-	-	-	-	-	3.62E+00	1.46E+02	-	3.90E+01	-4.68E+01	-	211

"-" = process not relevant

Table A6. Impacts of the different life cycle processes on marine eutrophication for the different scenarios.

	Marine eutrophication (kg N-equivalents)												
Scenario	In house storage	Anaerobic digestion	Upgrading	Substitution biogas	Separation	Storage solids	Storage liquids	Hygienization	Transport to recipient	Application solids	Application liquids	Avoided min fert recipient	Avoided min fert	Net impact
Ref	2.86E-02	-	-	-	-	-	-	-	-	-	8.79E-01	-	-1.90E-01	0.72
SP	2.85E-02	-	-	-	2.35E-05	2.02E-03	5.70E-03	5.59E-05	3.23E-03	2.04E-01	7.41E-01	-6.80E-02	-2.39E-01	0.68
DC	2.85E-02	-	-	-	9.20E-05	3.04E-03	6.83E-03	7.08E-05	4.09E-03	3.82E-01	6.38E-01	-1.06E-01	-2.20E-01	0.74
AD_SP	2.85E-02	7.97E-04	1.08E-04	-8.44E-03	2.31E-05	2.58E-03	7.18E-03	5.50E-05	3.18E-03	2.04E-01	7.64E-01	-7.97E-02	-2.84E-01	0.64
AD_DC	2.85E-02	7.97E-04	1.08E-04	-8.44E-03	9.05E-05	3.77E-03	6.72E-03	6.99E-05	4.04E-03	3.80E-01	6.59E-01	-1.25E-01	-2.61E-01	0.69
NoSep	2.86E-02	-	-	-	-	-	-	5.13E-04	2.96E-02	-	1.44E+00	-6.51E-01	-	0.85

Table A7. Impacts of the different life cycle processes on terrestrial acidification for the different scenarios.

	Terristrial acidification (kg SO2-equivalents)												
Scenario	In house storage	Anaerobic digestion	Upgrading	Substitution biogas	Separation	Storage solids	Storage liquids	Hygienization	Transport to recipient	Application solids	Application liquids	Avoided min fert recipient	Avoided min fert	Net impact
Ref	7.60E-01	-	-	-	-	-	-	-	-	-	2.90E+00	-	-1.18E-01	3.5
SP	7.60E-01	-	-	-	4.98E-04	5.39E-02	1.52E-01	1.18E-03	6.36E-02	4.63E-02	2.53E+00	-3.08E-02	-1.43E-01	3.4
DC	7.60E-01	-	-	-	1.95E-03	8.09E-02	1.82E-01	1.50E-03	8.06E-02	6.71E-02	2.41E+00	-7.05E-02	-1.35E-01	3.4
AD_SP	7.60E-01	1.26E-02	2.31E-03	-1.61E-01	4.90E-04	6.86E-02	1.91E-01	1.16E-03	6.26E-02	5.35E-02	3.20E+00	-3.45E-02	-1.71E-01	4.0
AD_DC	7.60E-01	1.26E-02	2.31E-03	-1.61E-01	1.92E-03	1.00E-01	1.79E-01	1.48E-03	7.96E-02	8.17E-02	3.02E+00	-7.56E-02	-1.59E-01	3.8
NoSep	7.60E-01	-	-	-	-	-	-	1.08E-02	5.83E-01	-	1.02E+00	-2.60E-01	-	2.1

Table A8. Impacts of the different life cycle processes on particulate matter formation for the different scenarios.

	Particulate matter formation (kg PM10-equivalents)												
Scenario	In house storage	Anaerobic digestion	Upgrading	Substitution biogas	Separation	Storage solids	Storage liquids	Hygienization	Transport to recipient	Application solids	Application liquids	Avoided min fert recipient	Avoided min fert	Net impact
Ref	9.96E-02	-	-	-	-	-	-	-	-	-	3.80E-01	-	-2.90E-02	0.45
SP	9.92E-02	-	-	-	2.22E-04	7.04E-03	1.98E-02	5.26E-04	3.49E-02	7.85E-03	3.32E-01	-8.83E-03	-3.35E-02	0.46
DC	9.92E-02	-	-	-	8.66E-04	1.06E-02	2.38E-02	6.66E-04	4.42E-02	1.11E-02	3.16E-01	-2.32E-02	-3.28E-02	0.45
AD_SP	9.92E-02	1.06E-02	9.76E-04	-9.40E-02	2.18E-04	8.96E-03	2.50E-02	5.18E-04	3.43E-02	8.77E-03	4.20E-01	-9.65E-03	-4.09E-02	0.46
AD_DC	9.92E-02	1.06E-02	9.76E-04	-9.40E-02	8.52E-04	1.31E-02	2.34E-02	6.58E-04	4.36E-02	1.29E-02	3.96E-01	-2.44E-02	-3.81E-02	0.44
NoSep	9.96E-02	-	-	-	-	-	-	4.82E-03	3.20E-01	-	1.38E-01	-6.96E-02	-	0.49

Table A9. Impacts of the different life cycle processes on fossil depletion for the different scenarios.

	Fossil depletion potential													
In house storage	In house storage	Anaerobic digestion	Upgrading	Substitution biogas	Separation	Storage solids	Storage liquids	Hygienization	Transport to recipient	Application solids	Application liquids	Avoided min fert recipient	Avoided min fert	Net impact
Ref	3.95E-02	-	-	-	-	-	-	-	-	-	1.73E-01	-	-2.91E+00	-2.7
SP	0.00E+00	-	-	-	4.13E-02	0.00E+00	0.00E+00	9.81E-02	5.73E+00	1.97E-01	1.73E-01	-8.23E-01	-3.28E+00	2.1
DC	0.00E+00	-	-	-	1.61E-01	0.00E+00	0.00E+00	1.24E-01	7.25E+00	2.49E-01	1.73E-01	-2.07E+00	-3.22E+00	2.7
AD_SP	0.00E+00	2.88E-01	2.15E-01	-9.59E+00	4.06E-02	0.00E+00	0.00E+00	9.65E-02	5.64E+00	1.94E-01	1.73E-01	-8.96E-01	-3.93E+00	-7.8
AD_DC	0.00E+00	2.88E-01	2.15E-01	-9.59E+00	1.59E-01	0.00E+00	0.00E+00	1.23E-01	7.16E+00	2.46E-01	1.73E-01	-2.17E+00	-3.69E+00	-7.1
NoSep	3.95E-02	-	-	-	-	-	-	8.99E-01	5.25E+01	-	5.94E-01	-6.37E+00	-	47.7

9. Scenario Analyses Results

Changing from P-based to an N-based fertiliser application on arable land

The lack of substantial change in impacts except P rock depletion can mainly be explained by the amount of avoided mineral N fertiliser not changing. The amount of manure spread per ha increased, which reduced the total spreading area, but the benefit from this was partly offset by a smaller amount of avoided mineral P fertiliser. The spreading area was ultimately determined by the EU Nitrate Directive, which applies for the recipient region and thus limited the manure N application to 170kg Tot-N/ha [1].

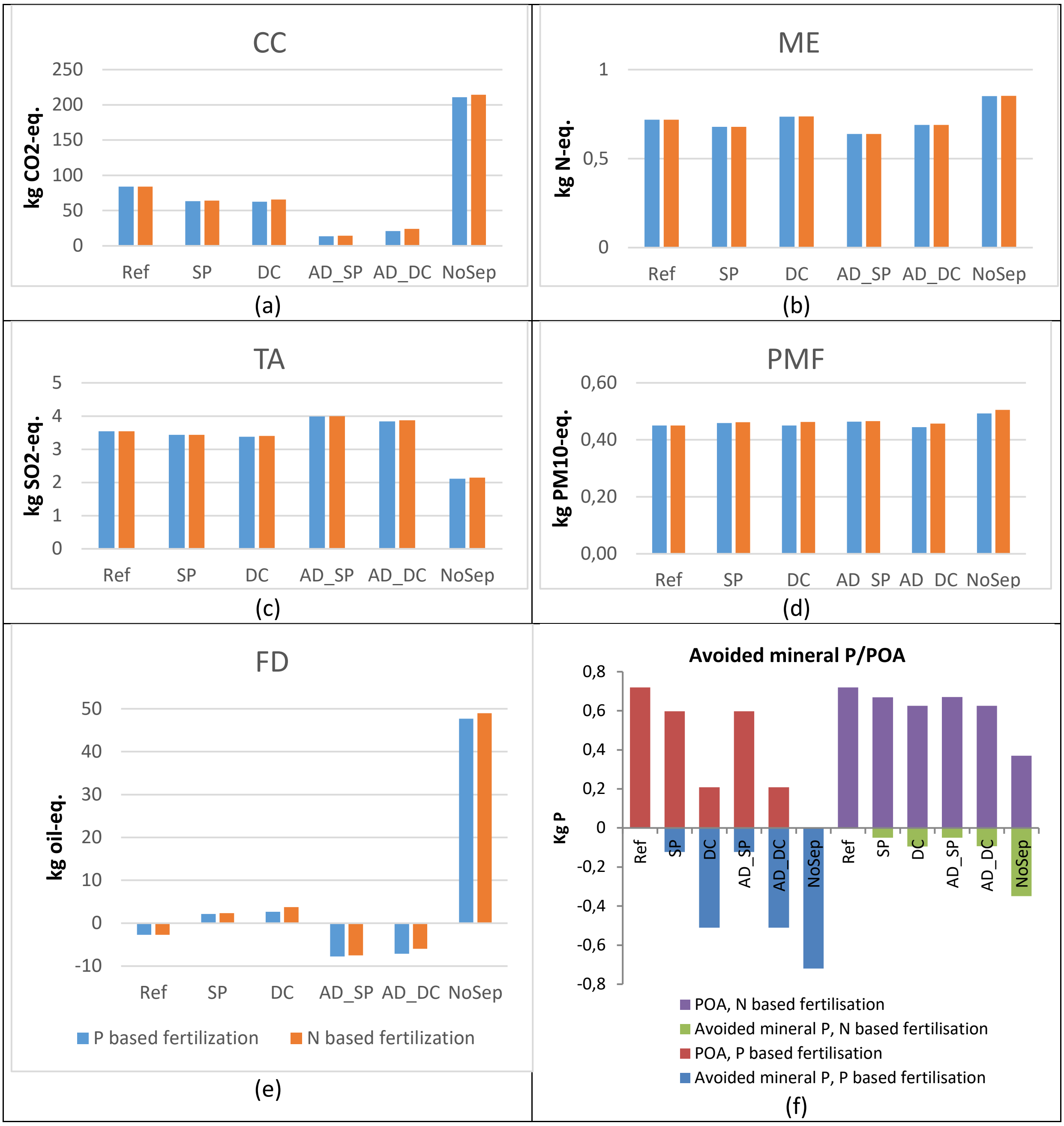

Figure A1. Results from changing the basis for manure fertilizer application in the recipient region from P-based to N-based. Net impacts are shown for: (a) climate change (CC); (b) marine eutrophication (ME); (c) terrestrial acidification (TA); (d) particulate matter formation (PMF); (e) fossil resource depletion (FD); (f) avoided mineral P/P over application (POA).

Optimal soil P levels at both the donor and recipient farm

Assuming an equal and optimal level of soil P level at the donor and recipient farm did not affect any of the impact categories to any notable extent. However, the assumption mostly eliminates any of the original motivation for P redistribution as the amount of avoided mineral P is almost the same between the reference scenario and the other redistribution scenarios.

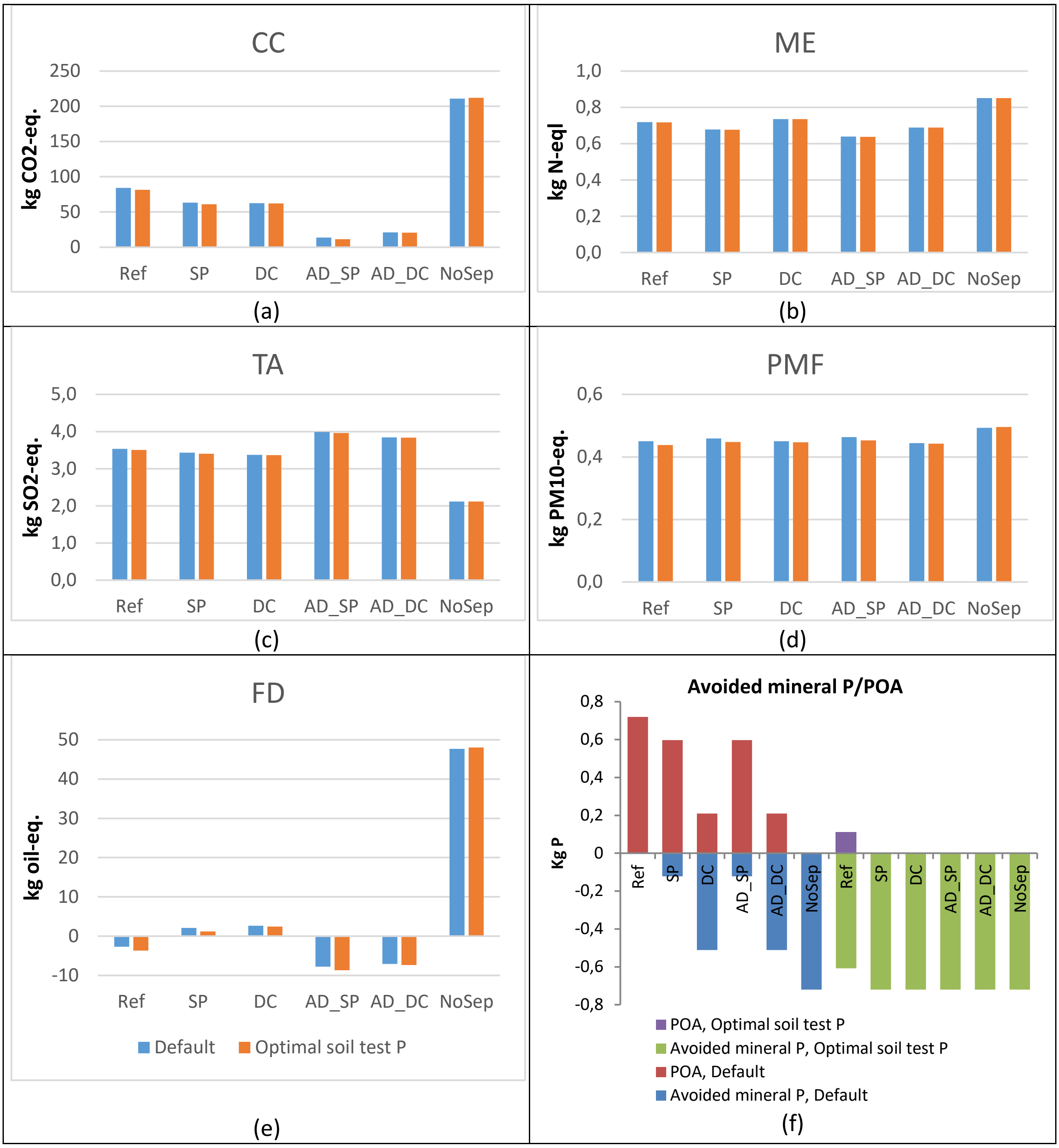

Figure A2. Results from changing the soil P levels at the donor and recipient farms from the default very high and moderately high, respectively, to optimal soil test P levels at both farms. Net impacts are shown for: (a) climate change (CC); (b) marine eutrophication (ME); (c) terrestrial acidification (TA); (d) particulate matter formation (PMF); (e) fossil resource depletion (FD); (f) avoided mineral P/P over application (POA).

Varying transport distance and mode

The underlying data for the scenario analysis on varying transport distance and mode are shown in Table A9, where climate change impact per tonne kilometre for the three transport modes have been estimated in SimaPro and converted to impact per kilometre for the mass transported in each of the three scenarios analysed. The impacts for four different transport distances are given in Table A10 together with the point of intersection with the reference scenario, i.e. the distance at which the net climate change impact of the reference scenario equals the net impact for a given scenario and transport mode.

Table A10. Potential climate change impacts per km of transported mass for three scenarios and three modes of transportation.

Scenario	Mass transported to recipient (kg)	Impact per km of transported mass (kg CO2-eq)		
		Lorry	Train	Ship
DC	238	0.0402	0.0044	0.0028
AD_DC	235	0.0397	0.0043	0.0027
NoSep	1723	0.2912	0.0317	0.0199

Table A11. Potential net climate change impacts for a given combination of scenario, transport mode and transport distance between donor and recipient. In the rightmost column, the distance at which the net climate change impact of the reference scenario equals the net impact for a given scenario and transport mode is given as the point of intersection.

Scenario	Transport mode	Net climate change impact for a given distance between donor and recipient farm (kg CO2-eq)				Point of intersection with Ref (km)
		0 km	500 km	1000 km	1500 km	
Ref	-	84	84	84	84	-
DC	Lorry	42	63	83	103	1035
	Train	42	45	47	49	9496
	Ship	42	44	45	47	15104
AD_DC	Lorry	1.4	21	41	61	2083
	Train	1.4	3.5	5.7	7.8	19111
	Ship	1.4	2.7	4.1	5.4	30398
NoSep	Lorry	65	211	356	502	65
	Train	65	81	97	113	594
	Ship	65	75	85	95	945

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