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RESEARCH ARTICLE

INTENSIFICATION OF GRASSLAND-BASED DAIRY PRODUCTION AND ITS IMPACTS ON LAND, NITROGEN AND PHOSPHORUS USE EFFICIENCIES

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SUPPLEMENTARY MATERIALS

Includes:

A. Assessment of nitrogen and phosphorus flows in dairy farms using the KringloopWijzer model
B. Overview of basic farm data
C. Results of regression and correlation analyses of farm characteristics and main nutrient performance indicators
D. References

A. Assessment of nitrogen and phosphorus flows in dairy farms using the KringloopWijzer model

The 'KringloopWijzer' model was developed to quantify the agronomic and environmental performances of commercial dairy farms. The outcomes of the model help dairy farmers to show authorities and the dairy industry the sustainability performance of their produced milk. From 2016 onward, the 'KringloopWijzer' model is mandatory for almost all dairy farms in the Netherlands. The origin of the model is based on long term research at experimental dairy farm 'De Marke'[1,2] and on research monitoring at pilot commercial dairy farms[3]. Farmers (or their advisors) have to complete the Kringloopwijzer by themselves. Mainly verifiable input data are used in the model, so as to limit the possibility of creating 'biased' output.

The N and P balances at farm level were based on the flows of N and P that enter and leave the farm (inputs and outputs; Table S1). In addition, the N and P balances of two important components (soil and herd) of a dairy farm were assessed (Fig. S1; Table S1). The N and P balances of the soil component were defined as the difference in N and P flows entering and leaving the soil via the soil surface. The N and P balances of the herd component were defined as the difference in N and P flows entering the herd via animal feed and leaving the herd via milk, animals (meat) and manure.

Mass flows entering (imports) and leaving (exports) the farm were derived from farm accounts. Nitrogen (N) and phosphorus (P) flows in imported and exported animals were estimated from the number of animals per category (cow, calf and heifer), assuming category-specific nutrient contents. Generally, data from farm accounts were also used for financial bookkeeping and/or for legislation rules and therefore these data can be seen as 'controlled data'. The nutrient composition of imported feeds (concentrates, roughage) was obtained from feed analysis reports and from suppliers. The N output in milk was quantified by frequent monitoring of protein contents (%) and milk production (L) by the milk processor. The P content in milk ($mg \cdot L^{-1}$) was a fixed value (0.97 $mg \cdot L^{-1}$); from 2019 the P content in milk is determined in each delivery and farm-specific estimates of the P content in milk are being made. In case of output of manure, the volume was weighted and nutrient content determined by an accredited laboratory. From each homegrown silage heap the volume was measured for an estimate of the amount of dry matter (DM) and samples were taken to determine their nutritive value by chemical analyses by accredited laboratories.

The calculations in the 'KringloopWijzer' model start with the herd component (Fig. S1), for which the energy requirements are estimated, as function of breed, age, milk production, reproduction, housing and grazing conditions. The composition of the ration is calculated through an optimization routine, on the basis of accounts of purchased feed (mainly concentrates), and the proportions of homegrown silage, grazing regime (grazing days and hours) and the changes in the amounts of forages in stock. How much feed (kg DM) is consumed by the whole dairy herd is the result of the energy requirement of the dairy herd, the proportions of available feed (concentrates, grass silage, maize silage, fresh grass) and the energy content of feed. The N- and P-intake by the herd depend on the energy/N and energy/P ratios in the feed. Second step is the calculation of the excretion of N and P by the herd, as the difference between total feed N and P intake minus the retention of N and P in milk and meat.

The yields from grassland and maize land (DM, N and P) is a 'backward-calculation' by subtracting the amounts of purchased feed from the total feed consumption (see above), taking into account losses associated with grazing, harvesting and conservation.

Inputs of mineral fertilisers to farm land were taken from invoices of purchases. Inputs of slurry, urine and dung to the farm land were calculated from total excretion, intensity of grazing, estimated gaseous N losses from housing and storages, and from the recorded export of manure. Ammonia losses from applied fertilisers and manure were calculated using standard emission factors depending on the method of application, the composition of the manure and the type of mineral fertiliser. A detailed description of algorithms of the KringloopWijzer can be found in De Vries et al.[4].

Table S1 Description of N and P flows within a dairy farming system according to the KringloopWijzer

N and P flows	Flows/Identifiers	Farm balance	Component	Balances
			Herd	Soil
Use[a] of animals	I1, C1	I	I	
Use of concentrates	I2, C2	I	I	
Use of roughage	I3, C3	I	I	
Use of manure	I4, C4	I		
Use of fertilizer	I5, C5	I		I
Biological N fixation	I6	I		I
Atmospheric deposition	I7	I		I
Applied manure to soil[b]	I8			I
Excreta during grazing[c]	I9			I
Field losses during harvest and grazing	I10			I
Intake homegrown feed[d]	O11		I	
Exported animals	O1	O	O	
Exported milk	O2	O	O	
Exported roughage/crop	O3	O		
Exported manure	O4	O		
Gross production of feed on farm[e]	O5			O
Gross production of manure[f]	O6		S	
Ammonia losses[g]	O7	O		
Surplus farm[h]	Equation 1	S		
Surplus soil[i]	Equation 5			S

Note: The letter I denotes an input, the letter O denotes an output, C denotes a change in stocks, and S denotes a surplus. Surplus was defined as 'losses' of N and P from either the whole farm, or components of the farm, i.e., herd and soil. The identifiers refer to the arrows in Fig. S1 and to the equations used for estimating the balances and the use efficiencies (see text).

[a] 'Use of' means that N and P flows imported (identifier 'I') are corrected for changes in stock (identifier 'C'), i.e., differences between stocks at the end and beginning of the year.

[b] Excluding ammonia losses from animal houses and during spreading.

[c] Excluding ammonia losses during grazing.

[d] Intake homegrown feed (fresh grass, silage maize, other); excluding harvesting, conservation (except for P), feeding and grazing losses.

[e] Gross N and P yield (silage, grazing); including harvesting, conservation (except for P), feeding and grazing losses.

[f] Including ammonia losses from animal houses, during grazing and during spreading.

[g] All ammonia losses from animal houses, during grazing and during spreading.

[h] Including all ammonia losses, accumulation and/or depletion in the soil, denitrification, leaching and run-off.

[i] Including accumulation and/or depletion in the soil, denitrification, leaching and run-off.

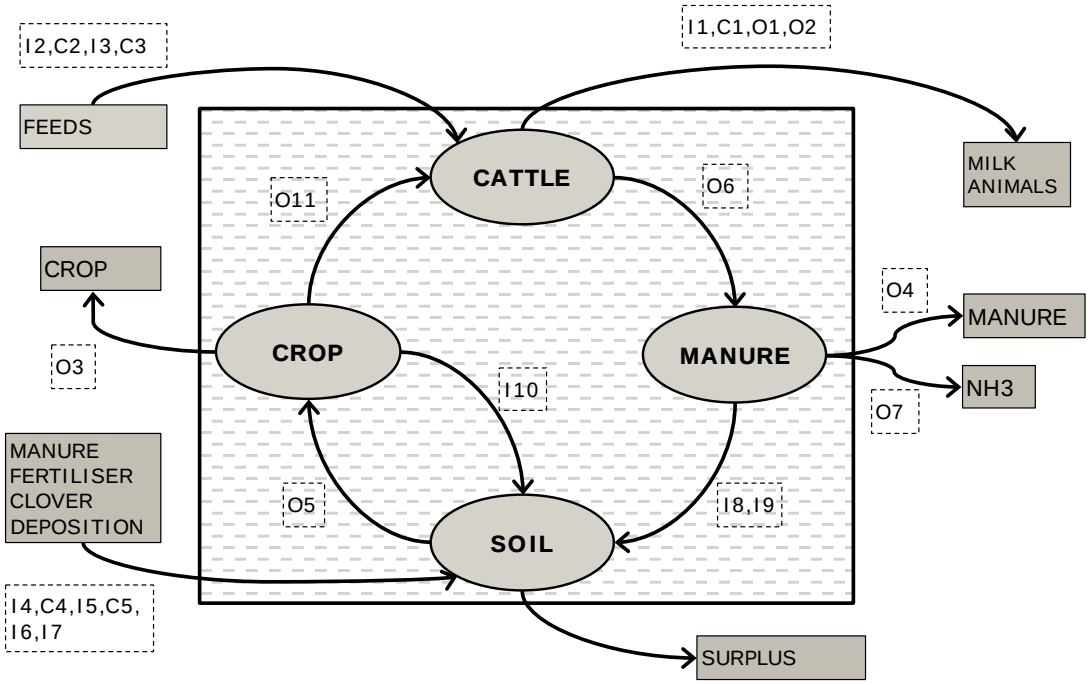

Fig. S1 Conceptual framework of N and P cycling in a dairy farm (indicated by the box), as applied in the KringloopWijzer. Farm N and P inputs, outputs and losses are presented in boxes outside the dairy farm; these are used to derive the farm input-output balance. The four components (cattle, manure, soil and crop) within the farm are connected via N and P flows (indicated by the arrows) and together represent the farm-internal cycling. The numbers in the dotted boxes refers to the N and P flow identifiers explained in Table S1 and each flow is assessed and recorded in the KringloopWijzer.

The N and P surplus ($kg \cdot ha^{-1}$) of the farm was calculated in the KringloopWijzer as follows:

$$\text{N and P surplus farm} = (I1 - C1 + I2 - C2 + I3 - C3 + I4 - C4 + I5 - C5 + I6 + I7) - (O1 + O2 + O3 + O4) \quad (1)$$

where I refers to the 'imported' inputs via animals (I1), concentrates (I2), roughage (I3), manure (I4), mineral fertilizer (I5), atmospheric N deposition (I6) and biological N_2 fixation (I7); C refers to N and P changes in stocks of animals (C1), concentrates (C2), roughages (C3), manure (C4) and mineral fertilizer (C5); and O refers to the outputs via animals (O1), milk (O2), roughage (O3) and manure (O4).

The NUE and PUE of the whole farm (%) was calculated as:

$$\text{N and P surplus farm} = 100 \times \frac{O1+O2+O3}{I1-C1+I2-C2+I3-C3+I4-C4-O4+I5-C5+I6+I7} \quad (2)$$

NUE and PUE farm were defined as output of milk, meat and roughage/crop divided by input of feed (concentrates and roughage), fertilizer, manure, atmospheric deposition (except for P) and biological N fixation (except for P). Inputs were corrected for changes in stock. Export of manure was considered as a (negative) input in the calculation of NUE and PUE

The total N and P input ($kg \cdot ha^{-1}$) at farm level was calculated as:

$$\text{Total N and P input} = I1 + I2 + I3 + I4 + I5 + I6 + I7 \quad (3)$$

Total N and P input ($kg \cdot ha^{-1}$) were defined as input of feed (roughage and concentrates), fertilizer, manure, atmospheric N deposition, and biological N_2 fixation. Inputs are not corrected for changes in stock.

The total N and P output (kg·ha^{-1}) at farm level was calculated as:

$$\text{Total N and P output} = O1 + O2 + O3 + O4 \quad (4)$$

Total N and P output (kg·ha^{-1}) were defined as output of milk, meat and roughage/crop and manure.

The N and P surplus (kg·ha^{-1}) of the soil compartment was calculated as:

$$\text{N and P surplus of the soil surface} = (I5 - C5 + I6 + I7 + I8 + I8 + I9 + I10) - O5 \quad (5)$$

where I refers to the inputs via imported mineral fertilizer (I5), atmospheric deposition (I6) (except for P), biological N fixation (I7) (except for P), applied manure (I8), excreta during grazing (I9), and field losses during harvest and grazing (I10); C refers to N and P changes in stocks of mineral fertilizer (C5); and O refers to the N and P outputs via gross roughage production before harvest and grass production before grazing (O5).

The NUE and PUE of the soil compartment (%) was calculated as:

$$\text{NUE and PUE soil} = 100 \text{ x } \frac{O5 - I11}{I5 - C5 + I6 + I7 + I8 + I8 + I9 + I10} \quad (6)$$

NUE and PUE soil were defined as output of net roughage production and grass production after grazing (O5-I11) divided by input of via applied mineral fertilizer (I5-C5) and manure (I8), atmospheric deposition (I6) (except for P), biological N fixation (I7) (except for P) and excreta during grazing (I9).

The NUE and PUE of the herd component (%) was calculated as:

$$\text{NUE and PUE herd} = 100 \text{ x } \frac{O1 + O2}{I1 - C1 + I2 - C2 + I3 - C3 + I11} \quad (7)$$

NUE and PUE herd (%) were defined as output of milk and meat (O1+O2) divided by input of imported animals and feed, corrected for changes in stock) (I1-C1+ I2-C2+ I3-C3) and intake of homegrown feed (O11).

The calculated annual N and P excretions and N and P yields of grassland and maize land were tested by comparing these values with measured data on 16 commercial pilot farms during a period of 10 years[5]. On these commercial pilot farms feed intake and milk production were measured for 6–10 weeks within a year, during periods that were representative for the feed intake (energy, N and P) of the herd during a whole year. The principal of the 'mass balance' (input minus output is surplus) was used; the N and P excretions were calculated by subtracting the measured input of feed from the calculated output of milk and the measured changes in weight of the whole herd.

Field-level data on dry matter yields and grazing were recorded for each cut. Dry matter yields were estimated for each mowing and grazing event, using a calibrated rising plate meter (Keuning, 1988). Silage maize dry matter yields were estimated at harvest, either by counting the number of loads and by weighing the loads. Samples from each silage heap were taken to determine their nutritive value by analyses in the laboratory. The monitoring of the yields were part of the monitoring of all substance flows on these commercial dairy farms. More information of the concept of the data calibration can be found in Oenema et al.[6].

On average the KringloopWijzer model underestimate the N and P excretions by 3% and 4% respectively (n = 138). The modelled N and P yields of grassland and maize land were on average within a range of 5%. Fig. S2 shows some of the results related to calculated N and P yields of grassland and measured N and P yields of grassland. The relationships were linear and the linear regression coefficients were close to 1[5].

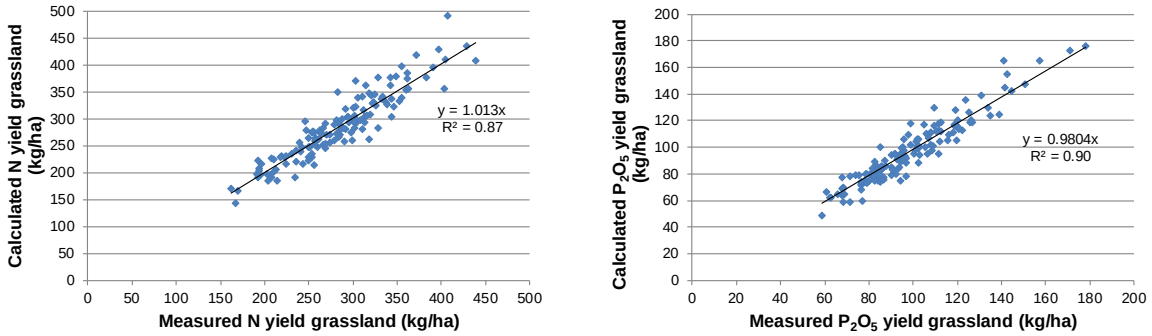

Fig. S2 Relationship between measured N and P_2O_5 yields and calculated N and P_2O_5 yields of grassland. Results obtained at 16 commercial dairy farms in the period 2006-2015. Yields were calculated by the KringloopWijzer[5].

B. Overview of basic farm data

Table S2 Overview of the dairy farm data from 2013 (1096 observations), 2014 (1597 observations) and 2015 (2858 observations)

Indicator	2013		2014		2015	
	Mean	s.d.	Mean	s.d.	Mean	s.d.
General farm characteristics						
Milk production (ha)	17205	5561	17258	5328	17993	5454
Total farm area (ha)	56	27	55	26	53	28
Share of grassland (%)	82	12	85	11	85	11
Total milk production (Mg·yr^{-1})	929	457	910	453	925	517
Milk production per cow (kg)	8375	927	8453	904	8477	961
Young stocks (number per 10 cows)	7.0	2.0	7.2	2.1	7.1	2.2
Grazing intensity (hours)	829	792	824	792	668	648
Indicators whole farm balance						
N surplus farm (kg·ha^{-1})	205	49	173	49	195	52
NUE farm (%)	35	8	40	9	38	9
N output via milk and animals (kg·ha^{-1})	110	35	114	35	121	37
N output manure (kg·ha^{-1})	39	60	48	61	68	83
N feed import (kg·ha^{-1})	203	113	204	114	215	110
P surplus farm (kg·ha^{-1})	4	7	–8	8	–2	8
PUE farm (%)	96	72	264	492	130	92
P output via milk and animals (kg·ha^{-1})	21	7	22	7	23	7
P output manure (kg·ha^{-1})	7	10	8	10	11	14
Indicators herd management						
NUE herd (%)	24.7	2.1	24.3	2.0	24.9	2.0
PUE herd (%)	31.8	2.9	31.8	2.8	31.9	2.7
Feed efficiency (kg FPCM per kg DM intake)	1.06	0.09	1.06	0.09	1.08	0.09
CP content in total feed ration (g per kg DM)	157	9	160	9	158	10
Indicators soil & crop management						
NUE soil (%)	66	11	74	11	68	12
PUE soil (%)	92	17	121	23	106	21
N surplus soil (kg·ha^{-1})	139	47	104	49	127	51
Dry matter yield grassland (kg·ha^{-1})	10479	2131	11682	2068	10805	2137
Dry matter yield silage maize (kg·ha^{-1})	16927	3367	18340	3425	18087	3182

Note: Mean indicator values and standard deviations of the mean (s.d.).

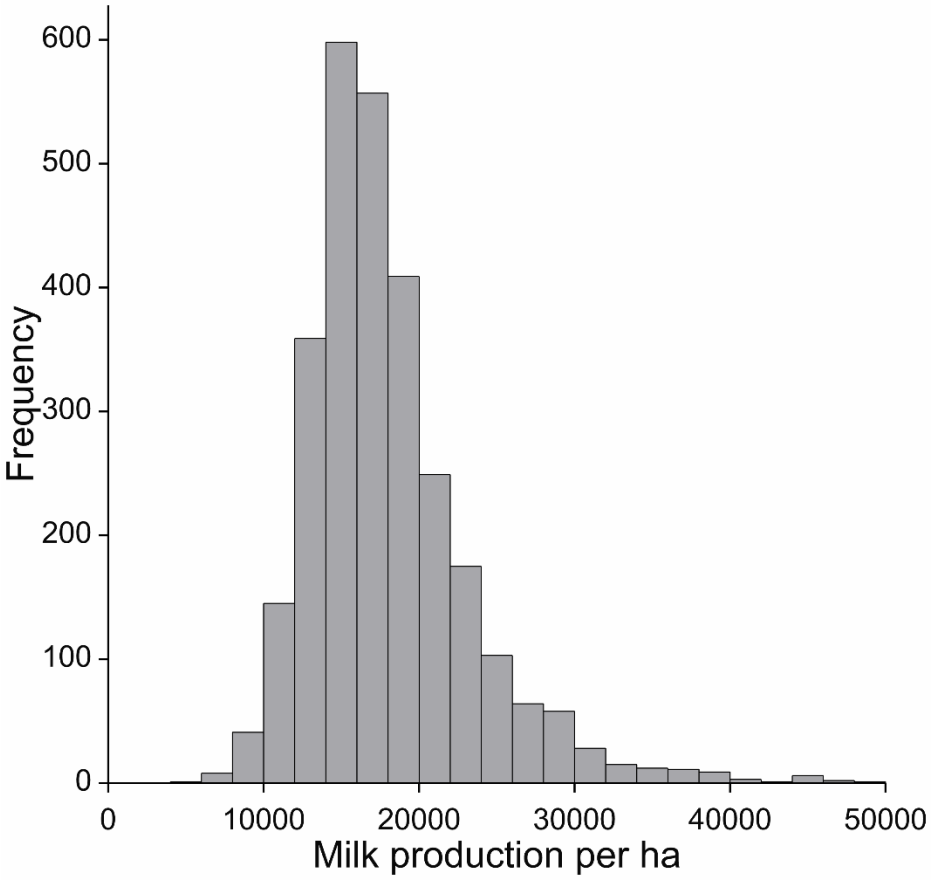

Fig. S3 Frequency distribution of milk production per ha of 2858 farms using data from 2015.

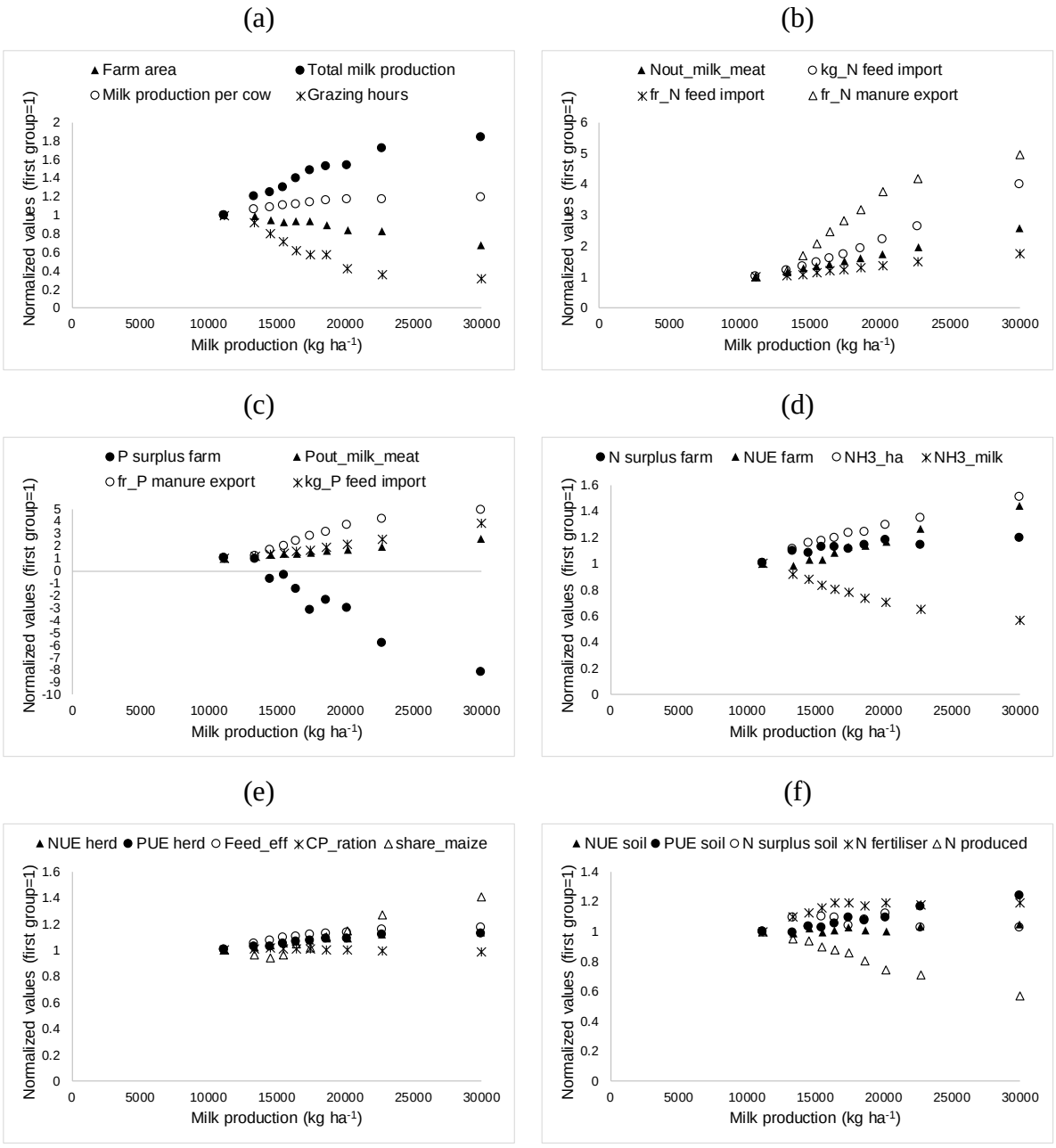

Fig. S4 Relationships between mean milk production per ha of farmland and normalized values of farm indicators. Results of 2858 farms using data from 2015. The 2858 farms were ordered in ascending order of milk production and then divided in 10 equal groups of 286 dairy farms. The mean indicator values of group 1 farms were set at 1.0. (a) Total farm area (ha), total milk production (Gg·yr^{-1}), milk production per cpw (kg), grazing intensity (hour)); (b) N output via milk and animals (kg·ha^{-1}), N feed import (kg·ha^{-1}), N feed import (% of total N input), N output manure (fraction of total N output); (c) P surplus farm (kg·ha^{-1}), P output via milk and animals (kg·ha^{-1}), P output manure (fraction of total P output), P feed import (kg·ha^{-1}); (d) N surplus farm (kg·ha^{-1}), NUE farm (%), total NH_3 emissions expressed as kg·ha^{-1} and as kg per Mg milk; (e) NUE and PUE herd (%), feed efficiency (kg FPCM per kg DM intake), crude protein content (CP) of feed ration (g per kg DM), share of maize in total feed ration, and (f) NUE and PUE soil (%), N surplus soil (kg·ha^{-1}), N mineral fertiliser to soil (kg·ha^{-1}), farm produced feed N (% of total N feed intake).

C. Results of regression and correlation analyses of farm characteristics and main nutrient performance indicators

Table S3 Estimated coefficients (slope) for indicators, with standard error of the slope (se) and the *P*-value for simple linear regression analysis with milk production ($Mg \cdot ha^{-1}$) for all 2858 dairy farms

Indicator	Slope	se	*P*-value
Total farm area (ha)	–0.971	0.093	< 0.001
Share of grassland (%)	0.040	0.037	0.286
Total milk production ($Mg \cdot yr^{-1}$)	0.028	0.002	< 0.001
Milk production per cow (kg)	64.8	3.1	< 0.001
Young stocks (number per 10 cows)	–0.096	0.007	< 0.001
Grazing intensity (hours)	–37.5	2.1	< 0.001
N surplus farm ($kg \cdot ha^{-1}$)	1.45	0.18	< 0.001
NUE farm (%)	0.82	0.027	< 0.001
Total N output ($kg \cdot ha^{-1}$)	18.3	0.2	< 0.001
N output via milk and animals ($kg \cdot ha^{-1}$)	6.46	0.04	< 0.001
N output manure ($kg \cdot ha^{-1}$)	11.9	0.2	< 0.001
N feed import ($kg \cdot ha^{-1}$)	18.5	0.1	< 0.001
P surplus farm ($kg \cdot ha^{-1}$)	–0.965	0.056	< 0.001
PUE farm (%)	1.55	0.32	< 0.001
Total P output ($kg \cdot ha^{-1}$)	7.38	0.08	< 0.001
P output via milk and animals ($kg \cdot ha^{-1}$)	2.85	0.02	< 0.001
P output manure ($kg \cdot ha^{-1}$)	4.54	0.07	< 0.001
Total NH3 emissions ($kg \cdot ha^{-1}$)	1.36	0.04	< 0.001
Total NH3 emissions (kg per Mg milk)	–0.104	0.003	< 0.001
NUE herd (%)	0.161	0.006	< 0.001
PUE herd (%)	0.202	0.009	< 0.001
Feed efficiency (kg FPCM per kg DM intake)	0.008	0.000	< 0.001
CP content in total feed ration (g per kg DM)	–0.188	0.033	< 0.001
share of maize in total feed ration (%)	0.576	0.037	< 0.001
Share of concentrates in ration (%)	0.370	0.021	< 0.001
NUE soil (%)	0.184	0.040	< 0.001
PUE soil (%)	1.34	0.07	< 0.001
N surplus soil ($kg \cdot ha^{-1}$)	–0.101	0.174	< 0.001
N manure to soil ($kg \cdot ha^{-1}$)	0.983	0.076	< 0.001
N mineral fertiliser to soil ($kg \cdot ha^{-1}$)	0.864	0.131	< 0.001
P manure to soil ($kg \cdot ha^{-1}$)	–0.112	0.018	< 0.001
P mineral fertiliser to soil ($kg \cdot ha^{-1}$)	–0.002	0.008	0.76
Dry matter yield grassland ($Mg \cdot ha^{-1} \cdot yr^{-1}$)	0.088	0.007	< 0.001
Dry matter yield silage maize ($Mg \cdot ha^{-1} \cdot yr^{-1}$)	–0.017	0.012	0.154
Farm produced feed N (% of total N feed intake)	–1.54	0.03	< 0.001

Table S4 Results of multiple regression analyses using data of all 2858 dairy farms; results of three regression models are presented: A, B and C

Regression analysis A

Response variate: NUE_farm

Fitted terms: Constant + Milk production (ha)+ NUE soil (%)+ NUE herd (%)

Table S4-1 Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	3	188842	62947.18	3745.50	< 0.001
Residual	2854	47965	16.81		
Total	2857	236806	82.89		

Note: Percentage variance accounted for 80 and Mallows' Cp values is 357.

Table S4-2 Estimates of parameters

Parameter	Estimate	s.e.	t(2854)	t pr.
Constant	–41.87	1.15	–36.54	< 0.001
Milk production	0.000521	1.58E-05	32.98	< 0.001
NUE soil	0.5914	0.00674	87.76	< 0.001
NUE herd	1.2139	0.0425	28.56	< 0.001

Regression analysis B

Response variate: NUE_farm

Fitted terms: Constant + NUE soil (%) + N feed import (kg ha^{-1} yr^{-1}) + NUE herd (%) + N output via milk and meat (kg ha^{-1} yr^{-1})

Table S4-3 Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	4	197171	49292.9	3548.22	< 0.001
Residual	2853	39635	13.89		
Total	2857	236806	82.89		

Note: Percentage variance accounted for 83 and Mallows'Cp value is 112.

Table S4-4 Estimates of parameters

Parameter	Estimate	s.e.	t(2853)	t pr.
Constant	–45.1	1.04	–43.21	< 0.001
NUE soil	0.58001	0.00614	94.43	< 0.001
N feed import	0.19292	0.00807	23.9	< 0.001
NUE herd	1.1479	0.0385	29.82	< 0.001
N output milk + meat	0.04053	0.00262	15.45	< 0.001

Regression analysis C: model with the highest adjusted R^2 and lowest Mallows'Cp-value

Response variate: NUE_farm

Fitted terms: Constant + NUE soil (%) + N feed import ($kg \cdot ha^{-1} \cdot yr^{-1}$) + NUE herd (%) + N output via milk and meat ($kg \cdot ha^{-1} \cdot yr^{-1}$) + CP content in total feed ration (g per kg DM) + Young stocks (number per10 cows) + Grazing intensity ($h \cdot yr^{-1}$)

Table S4-5 Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	7	197883	28269.1	2069.92	< 0.001
Residual	2850	38923	13.66		
Total	2857	236806	82.89		

Note: Percentage variance accounted for 84, and Mallows'Cp value is 7.

Table S4-6 Estimates of parameters

Parameter	Estimate	s.e.	t(2850)	t pr.
Constant	–39.31	2.86	–13.75	< 0.001
NUE bod	0.58247	0.0061	95.43	< 0.001
N feed import	0.18126	0.00822	22.06	< 0.001
NUE herd	1.0918	0.0541	20.19	< 0.001
N output milk + meat	0.04381	0.00268	16.37	< 0.001
CP in total feed ration	–0.0328	0.0101	–3.26	< 0.001
Young stocks	0.1427	0.0384	3.72	< 0.001
Grazing intensity	–0.0003	0.00012	–2.19	0.029

Table S5 Correlations between main farm characteristics and main nutrient performance indicators of 2858 dairy farms in 2015

Indicator	Nr	Indicator									
		1	2	4	5	6	7	8	9	13	14
Milk production ($Mg \cdot ha^{-1}$)	1										
Land area (ha)	2	–0.18									
Total milk production ($Gg \cdot yr^{-1}$)	4	0.32	0.83								
Milk production per cow (kg)	5	0.36	0.14	0.31							
Young stocks (number per 10 cows)	6	–0.24	0.07	–0.06	0.00						
Grazing intensity ($h \cdot yr^{-1}$)	7	–0.32	–0.12	–0.27	–0.25	–0.05					
N surplus farm ($kg \cdot ha^{-1} \cdot yr^{-1}$)	8	0.16	0.02	0.10	0.09	–0.03	–0.02				
N use efficiency farm (%)	9	0.49	–0.12	0.13	0.19	–0.11	–0.24	–0.67			
P surplus farm ($kg \cdot ha^{-1} \cdot yr^{-1}$)	13	–0.31	0.03	–0.15	–0.15	–0.02	0.17	0.54	–0.64		
P use efficiency farm (%)	14	0.10	0.00	0.07	0.04	0.04	–0.08	–0.38	0.37	–0.63	
Feed efficiency (kg FPCM per kg DM intake)	19	0.43	0.01	0.22	0.62	–0.73	–0.17	0.07	0.24	–0.07	–0.01

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