Agrociencia Uruguay 2024 | Volume 28 | Number NE1 | Article e1243
DOI: 10.31285/AGRO.28.1243
ISSN 2730-5066

Advances and trends of dairy production in Uruguay

Balancing nitrogen at the farm gate: Economic-environmental sustainability trade-off in pastoral dairy systems of Uruguay

Stirling, S.[1]; Lussich, F. [1 4]; Ortega, G. [2]; La Manna, A. [1]; Pedemonte, A. [3]; Artagaveytia, J. [3]; Guidice, G. [3]; Fariña, S.[1]; Chilibroste, P.[2]; Lattanzi, F. A.[1]

[1]Instituto Nacional de Investigación Agropecuaria (INIA), Colonia, Uruguay
[2]Universidad de la República, Facultad de Agronomía, Paysandú, Uruguay
[3]Instituto Nacional de la Leche, Montevideo, Uruguay
[4]University of Tennessee, Department of Biosystems Engineering and Soil Science, Knoxville, USA

Editor

Mariana Carriquiry
Universidad de la República, Montevideo, Uruguay

Received *04 Sep 2023*
Accepted *20 Feb 2024*
Published *23 May 2024*

Correspondence

Sofia Stirling
sstirling@inia.org.uy

Abstract

Uruguay´s dairy can potentially enhance milk productivity competitively, but intensification risks elevating nitrogen (N) surplus, heightening environmental concerns. This study quantified farm-gate N inputs and outputs, calculating N surplus (input-output) and N use efficiency (NUE=output/input) for 17 commercial modal dairy systems identified in the 2014 and 2019 national surveys and six prospective intensified systems based on experimental pastoral farmlets achieving near-maximal rainfed productivity. Current dairy systems maintained N surplus at 71 kg N ha^{-1} between 2014 and 2019 (range: 44-97 kg N ha^{-1}) while improving NUE from 28.3 to 30.5% (range: 20-35%). Intensification increased N surplus without necessarily reducing NUE. Our analyses highlight three aspects: (i) comparatively low N surplus of current Uruguayan dairy, (ii) nonlinear links between N surplus and stocking rate, feed intake, milk productivity and operating profit, and (iii) inequality between dairy systems in their contribution to national dairy N surplus reflects mainly disparity in farm size. These insights underscore the crucial need for understanding the actual fate of N surpluses: nitrate leaching, ammonia volatilisation, N_2 denitrification, or N accumulation in soil organic matter. This is an unavoidable requisite for designing management practices and policies able to effectively optimise the economic and environmental sustainability of Uruguayan dairy.

Keywords: grazing systems, whole-farm balance, N losses, N surplus, N use efficiency

Balanceando el nitrógeno en la portera del predio: Sostenibilidad económica y ambiental en los sistemas lecheros pastoriles de Uruguay

Resumen

La lechería uruguaya presenta la oportunidad de mejorar la competitividad en la productividad de leche. Sin embargo, la intensificación aumenta el riesgo de elevar el excedente de nitrógeno (N) y la contaminación ambiental. Este estudio

Stirling S, Lussich F, Ortega G, La Manna A, Pedemonte A, Artagaveytia J, Guidice G, Fariña S, Chilibroste P, Lattanzi, FA. Balancing nitrogen at the farm gate: Economic-environmental sustainability trade-off in pastoral dairy systems of Uruguay. Agrociencia Uruguay [Internet]. 2024 [cited dd mmm yyyy];28(NE1):e1243. Doi: 10.31285/AGRO.28.1243.

evaluó las entradas y salidas de N predial, N excedente (entrada-salida) y eficiencia de uso de N (NUE=salida/entrada) de 17 sistemas modales (encuestas nacionales 2014–2019), y 6 sistemas intensificados basados en estudios experimentales de alta productividad de leche por hectárea en secano. Los sistemas lecheros actuales mantuvieron un N excedente de 71 kg N ha^{-1} entre 2014 y 2019 (rango: 44-97 kg N ha^{-1}), y mejoraron la NUE de 28,3 a 30,5% (rango: 20-35%). De nuestro análisis se destacan tres puntos: (i) el N excedente comparativamente bajo de la lechería uruguaya actual, (ii) las relaciones no lineales entre N excedente y carga animal, consumo de alimento, productividad de la leche e ingreso de capital, y (iii) la contribución desigual entre los sistemas lecheros al excedente nacional de N de la lechería refleja principalmente la disparidad en el tamaño de los predios. Estos hallazgos evidencian la necesidad crucial de entender el destino real de los excedentes de N: lixiviación de nitratos, volatilización de amoníaco, desnitrificación de N_2 o acumulación de N en materia orgánica del suelo. Este es un requisito ineludible para diseñar prácticas y políticas de gestión capaces de optimizar efectivamente la sostenibilidad económica y ambiental de la lechería uruguaya.

Palabras clave: balance predial de N, contaminación, sistemas lecheros

Equilibrando o nitrogênio no portão da propriedade: Sustentabilidade econômica e ambiental nos sistemas leiteiros pastoris do Uruguai

Resumo

A pecuária leiteira uruguaia apresenta a oportunidade de melhorar a competitividade na produtividade do leite. No entanto, a intensificação aumenta o risco de elevar o excesso de nitrogênio (N) e a poluição ambiental. Este estudo avaliou as entradas e saídas de N na propriedade, o excesso de N (entrada-saída) e a eficiência de uso de N (NUE = saída/entrada) de 17 sistemas modais (pesquisas nacionais 2014–2019) e seis sistemas intensificados com base em estudos experimentais de alta produtividade de leite por hectare em sequeiro. Os sistemas leiteiros atuais mantiveram um excesso de N de 71 kg N ha^{-1}entre 2014 e 2019 (faixa: 44-97 kg N ha^{-1}) e melhoraram a NUE de 28,3% para 30,5% (faixa: 20-35%). De nossa análise, destacam-se três pontos: (i) o excesso de N comparativamente baixo na pecuária leiteira uruguaia atual, (ii) relações não lineares entre o excesso de N e carga animal, consumo de alimentos, produtividade do leite e entrada de capital, e (iii) a contribuição desigual entre os sistemas leiteiros para o excesso nacional de N da pecuária leiteira reflete principalmente a disparidade no tamanho das propriedades. Essas descobertas evidenciam a necessidade crucial de entender o destino real dos excessos de N: lixiviação de nitratos, volatilização de amônia, desnitrificação para N^2 ou acumulação de N na matéria orgânica do solo. Este é um requisito inegociável para projetar práticas e políticas de gestão capazes de otimizar efetivamente a sustentabilidade econômica e ambiental da pecuária leiteira uruguaia.

Palavras-chave: balanço de N, poluição, sistemas leiteiros

1. Introduction

Intensive dairy production is debated because of its roles in resource utilisation, nitrogen (N) pollution of the environment, greenhouse gas emissions, and their impacts on landscape and biodiversity(1). Concerning N cycling, the intensification of dairy production has been linked to an increase in N surplus, a decrease in nitrogen use efficiency (NUE), and the accumulation of N in the soil. This occurs because NUE in dairy production is limited by the biological capacity of cows to convert N from feed into milk, and by the ability of crops and pastures to transform soil N into grains, forage, and other agricultural products(2). The surplus N in the system that is not absorbed by plants or utilised by animals can result in detrimental environmental consequences, including water pollution from nitrate leaching, global warming due to nitrous oxide emissions, and air pollution from ammonia emissions(3).

In this regard, the strong association between intensification *via* higher stocking rates and pasture production per hectare and N surplus has been widely reported in intensified pasture-based dairy systems such as those from New Zealand(4), Australia(5), The Netherlands(6) or Ireland(7). This situation has led to water pollution due to the leaching of N from urine and fertilizer deposited on pasture in countries with predominantly permeable soils, such as Ireland and New Zealand(8)(9)(10).

The Uruguayan dairy presents the opportunity to increase productivity per hectare but with the challenge of maintaining competitiveness and ensuring the sustainability of natural resources(11)(12). Uruguay exports around 70% of total milk production to the international dairy market(13) and is positioned as the seventh largest milk exporting country worldwide(14). Therefore, the future of the dairy sector relies on its ability to remain competitive domestically and internationally. Dairy farm systems in Uruguay present the opportunity to increase milk production through improved utilisation of home-grown forage by increasing the stocking rate(11). National research studies show that a two-fold increase in stocking rate from the industry average is biologically feasible and significantly improves dairy systems' biophysical and economic performance(15)(16)(17). These results have encouraged and provided a clear direction for the intensification of commercial dairy systems. These proposed prospective intensification strategies combine stocking rates, cow genotypes, and feeding strategies. Overall, they are characterised by increased stocking rates, home-grown forage harvest per hectare, and reliance on N fertilizers and imported supplements. In this regard, the environmental impact of such strategies in terms of N use remains unclear(11)(18).

The objective of the present study was to assess the magnitude of farm-gate N surpluses and NUE in dairy farms from Uruguay. The aim was to consolidate information regarding the performance of current and prospective dairy systems in terms of basic N indicators to help optimise the trade-off between economic and environmental sustainability.

2. Materials and methods

The farm-gate balance of 23 representative Uruguayan dairy farm systems was evaluated. The farm systems evaluated were: (i) 17 commercial modal dairy systems classified from two national dairy surveys, and (ii) 6 prospective intensified systems scaled up from experimental farmlets data.

2.1 Data sources

2.1.1 Modal dairy systems

The modal dairy systems are typologies of representative systems of the Uruguayan dairy sector developed by the National Milk Institute (INALE) Technical Team, based on farm scale (annual milk production), land productivity (L ha^{-1}), and pasture harvest (kg DM ha^{-1}) (the latter only applies for the 2014 modal systems) (**Table S1**, Supplementary material).

Data from national dairy surveys conducted in 2014 and 2019 by INALE and the Ministry of Livestock, Agriculture and Fisheries (MGAP) were used to develop these typologies. The survey included farms located in the main dairy regions of Uruguay (i.e., Canelones, Colonia, Flores, Florida, Paysandú, Río Negro, San José and Soriano). A total of 314 and 294 farms were surveyed in 2014 and 2019, respectively. This accounted for more than 80% of national overall milk production; therefore, we will refer to the results based on this data as the national average(19)(20). The information surveyed included farm area, animal stocks and reconciliation, land use, milk and live weight productivity, feeding, pasture utilisation, silage and concentrate production and purchases and fertilizer purchases.

Seven modal systems were defined from the 2014 survey (i.e., ML1, ML2, ML4, ML6, ML8, ML10, ML12) and 10 from the 2019 survey (i.e., M1, M2B, M2A, M3B, M3A, M4B, M4A, M5B, M5A, M6). The economic analysis was performed on the modal dairy farms for the 2019-20 financial year. The classification criteria and detailed information about each modal dairy system are presented in **Table S1** and **Table S2**. The national average was calculated as the milk production-weighted of all modal dairy farm systems surveyed in 2014 and 2019.

2.1.2 Experimental farmlets

The intensified systems evaluated in this study arise from the "CRS" and "10MIL" farmlet studies. Both farmlet studies assessed the biophysical feasibility and economic result of intensification options to increase milk production per hectare well above the average national dairy farm. The information from each farmlet (three-year data) was scaled up to the average Uruguayan modal dairy farm (i.e., M4; 145 ha farm) as part of a study carried out by INALE to assess the economics of technological research proposal adoption. It was simulated that the average Uruguayan modal dairy farm (M4) "adopted" the CRS and 10MIL research systems (i.e., farm system design, stocking rate, feeding strategies, labour, infrastructure, fertilization rates, investments, etc.) to achieve similar productive and economic results. This methodology enabled us to compare the modal dairy systems and the experimental farmlets.

A detailed description of the "10MIL" farmlet study is provided by Stirling and others**(16)**. Briefly, the farmlets were located at INIA La Estanzuela (34°20'S, 57°41'W, Uruguay) and evaluated for three years (Seasons 2017/18, 2018/19 and 2019/20) the biophysical performance of intensification strategies based on increasing home-grown forage harvest to sustain a two-fold increase in stocking rate relative to the national average. Specifically, this study evaluated two feeding strategies with varying proportions of grazing in the annual feeding budget [grass fixed (GFix) and grass maximum (GMax)] and two Holstein Friesian cow genotypes [New Zealand (NZHF) or North American Holstein Friesian (NAHF)]. The farmlets evaluated were GMax-NAHF, GMax-NZHF, GFix-NAHF, and GFix-NZHF.

The "CRS" farmlet study was conducted at the Centro Regional Sur research station, Agronomy Faculty, Canelones, Uruguay**(21)** (34°36.8' S, 56°13.1' W). The experiment involved four whole-farm systems evaluated for three years (Seasons 2016/17, 2017/18 and 2018/19). This study evaluated two stocking rates (SR): 1.5 or 2.0 milking cows per ha^{-1} of milking platform (i.e., 1.4 and 1.7 cows per ha^{-1} of dairy area) combined by two contrasting residual sward heights: 4 cm residual sward height all year round (Low Residual, LR) or seasonally variable residual sward height (6 cm for autumn and winter, 9 cm for spring and 12 cm for summer) (High Residual, HR). Thus, four treatments resulted from combining the two factors: 1.5LR, 1.5HR, 2.0LR and 2.0HR. For this study, the average SR treatments were analysed as no apparent differences were observed between the LR and HR treatments for the "CRS" farmlets.

2.2 Farm systems characteristics

The modal dairy systems and scaled-up experimental farmlets will be referred to as dairy farm systems. The farm systems descriptions with key productive and economic performance indicators for the modal and intensified dairy systems are given in **Table 1**. The national average dairy systems (2014 and 2019) present an average of 1.0 cows ha^{-1} and produce 415 kg milk solids ha^{-1}. The intensified systems ("CRS" and "10MIL") present, on average, a two fold increase in stocking rate (1.8 cows ha^{-1}) and solids productivity per ha (1,000 kg milk solids ha^{-1}) regarding the national average.

All the systems studied presented common features of typical dairy farming in Uruguay. Around 60% of the total farm area is occupied by long-term mixed pastures that last 3-4 years, and the rest is occupied by annual pastures (i.e., oats, ryegrass) and crops (i.e., sorghum, maize) destined for grazing and silage or grain production. While most of the silage is produced on-farm, these systems rely on purchased concentrate (82-100% bought-in). Generally, supplements are offered on a feed pad or sacrifice paddock where cows are confined during pasture shortage seasons, and when access to pasture is constrained due to weather events. Inorganic fertilizer is imported and applied to pastures and crops in these systems.

Table 1. Description of the national average dairy systems (2014 and 2019) and the “CRS” and “10MIL” intensified dairy systems

	NATIONAL DAIRY SYSTEMS[1]				INTENSIFIED DAIRY SYSTEMS					
	2014		2019		“CRS”		“10MIL”			
Farm characteristics	Mean	SD	Mean	SD	CRS 1.5	CRS 2.0	GFix-NAHF	GFix-NZHF	GMax-NAHF	GMax-NZHF
Farm area (ha)	276	164	350	230	145	145	145	145	145	145
Total cows (number)	280	166	377	262	206	253	273	332	260	316
Stocking rate (cows ha^{-1})	1.02	0.16	1.05	0.19	1.42	1.74	1.88	2.29	1.79	2.18
Milk solids (kg MS ha^{-1})	403	123	427	143	713	916	1,183	1,256	1,099	1,259
Land use (% total area)										
Mixed pastures	54	4	61	4	68	61	65	64	74	73
Annual pastures/crops	33	7	29	5	23	24	16	16	17	17
Crops	13	4	10	3	10	15	19	21	8	10
Feed intake (Mg DM ha^{-1})										
Concentrates	1.6	0.6	1.4	0.5	2.5	3.3	4.3	4.4	4.3	4.5
Silage	1.9	0.4	1.3	0.4	2.1	3.0	4.4	5.3	1.9	2.3
Pasture	3.0	0.8	3.4	0.7	3.9	4.3	4.8	4.9	6.6	7.6
Homegrown forage (Mg DM ha^{-1})	4.8	0.9	4.6	1.0	5.8	6.8	9.3	10.2	8.5	9.8
Bought-in concentrate (%)	82	5	92	10	100	100	100	100	100	100
Bought-in silage (%)	5	7	7	11	10	17	0	0	0	0
Operating profit (US$ ha^{-1})	476	150	407	179	536	793	1,016	980	1,094	1,437

[1] The national average was calculated as the milk production-weighted of all modal dairy farm systems surveyed in 2014 and 2019.

2.3 Farm-gate balance calculation

The balance presented in this study involved calculating N inputs and N outputs at the farm-gate according to the guidance document developed by the EU N Expert Panel(22), as it is widely used in science and policy. Nitrogen surplus was calculated as the difference between total N inputs and total N outputs and expressed on a per-hectare basis. Nitrogen use efficiency was calculated as the ratio of total N outputs divided by total N inputs and expressed as a percentage.

All N input and output data were collected in individual farms and expressed in kg N ha^{-1} of farm area yr^{-1}. The unit of land considered for this study was the dairy area, defined as the area destined for the milking cows plus the area destined for the dry stock.

2.3.1 Nitrogen imports

Inputs comprised N entering the farm as mineral fertilizer, imported concentrates and silage, biological N fixation and atmospheric deposition. Nitrogen imported in mineral fertilizers was calculated from the amount of chemical fertilizer purchased. Standard N concentrations, as provided by commercial suppliers, were used. Nitrogen entering the farm in concentrate and silage feeds was established by multiplying the total quantity purchased by the crude protein content, using specific values for the modal dairy systems and the farmlet studies, divided by 6.25(23).

For biological N_2 fixation calculation, a value of 36.5 kg N fixed per Mg of DM legume consumed by animals was used(24) (**Supplement S3**). The amount of consumed legume DM was estimated by calculating total pasture harvested (Mg DM ha^{-1} yr^{-1}) as the sum of grazed pasture and pasture harvested as forage reserves and then affected by the percentage of the area with grass/legume mixed pastures, which was reported in surveys and measured in farmlets. Afterwards, 40% of legume DM in the mixed pasture was assumed for modal systems, as the survey did not include this data (**Supplement S3**). For farmlets, the measured proportion of legume DM in mixed pastures was used. Nitrogen atmospheric deposition values were taken for two locations in Uruguay(25).

Nitrogen from silage surplus was calculated as the difference between total silage imported and produced and silage consumed and the average N concentration of silage. It was considered a “negative input” rather than an output, according to the guidelines suggested by de Klein and others(9).

2.3.2 Nitrogen exports

Nitrogen outputs included milk and live weight production. Nitrogen exported in milk was calculated from the annual amount of milk produced and the crude protein milk concentration divided by 6.38(26). Nitrogen export in livestock was calculated from the difference in live weight between the replacement heifers entering the farm and culled cows leaving the farm multiplied by a standard 0.024% N concentration in live weight of adult animals(26).

2.3.3 Statistical analysis

Regression analysis was undertaken to describe the relationship between the components of the farm-gate N balance and between N surplus and the productive and economic variables used to characterise the systems. The goodness of fit of fitted models was assessed using the coefficient of determination (R^2) adjusted by the number of parameters and the residual mean squared error. Power models fitted the data with similar or better goodness-of-fit than linear models. The power regression model used was $y = c + a\,x^b$, where y is the dependent variable, x is the independent variable, and the fitted parameters a, b and c are the scaling coefficient, the exponent coefficient, and the intercept, respectively. The exponent coefficient is particularly relevant as it indicates the degree of non-linearity (how far it is from 1) and the shape of the curvature (increasing when >1, decreasing when <1). All analyses were carried out in TBL Curve v5.01 (Systat), using the Levenberg–Marquardt algorithm to iteratively minimise squared residuals.

2.3.4 Contribution of the 2019 modal dairy farms to total national dairy N surplus

The contribution of each modal dairy farm (2019) to the total N surplus in Uruguay was assessed by plotting the cumulative proportion of total milk production and total number of dairy farms in Uruguay vs. the cumulative proportion of total N surplus.

Gini plots were generated by linear interpolation of the cumulative proportions of milk production, number of farms and N surplus. These plots provide a visual and quantitative depiction of the degree of inequality of dairy modal systems to the national dairy N surplus. The Gini coefficient was calculated(27), ranging from 0 (perfect equality) to 1 (perfect inequality).

2.3.5 Targets for nitrogen performance indicators

Nitrogen input and output values of the assessed systems were mapped onto the framework proposed by the EU Nitrogen Expert Panel(22). Furthermore, we mapped pastoral dairy systems from primary exporting dairy countries in the same plot(9). This approach allows the analysis of farm performance simultaneously in terms of its NUE, N output, and N surplus, providing a graphical assessment of the distance between actual and possible target values for each indicator for each system.

For N output, two minimum thresholds were defined based on the milk solids productivity per hectare that a dairy farm system must achieve to be profitable in Uruguay. The long-term sustainability of a dairy farm is achieved when the operating profit can remunerate the land and capital factors. For the calculation of remuneration: (i) land is treated as if it is all leased at an average market value of 160 US\$ ha^{-1}; (ii) capital (livestock, machinery, and improvements) is remunerated at an annual interest rate of 4%, which amounts to 108 US\$ ha^{-1}. According to this, a dairy farm's minimum acceptable operating profit in the 2021/22 period was calculated as 268 US\$ ha^{-1}. For comparison, the operating profit of agricultural systems —which would compete for land with dairy systems— averaged 251 US\$ ha^{-1} over the last ten years (FUCREA, *Federación Uruguaya de grupos CREA*; *pers. comm.*). Therefore, dairy systems below the 250-270 US\$ ha^{-1} threshold (i.e., N output below 19 and 21 kg N ha^{-1}) are deemed to have their economic sustainability compromised.

Maximum and minimum thresholds for NUE were set at 20% and 60%, according to targets proposed for mixed crop-livestock systems, where both crop and livestock products are included(28). Mixed crop-livestock production systems will have different target values than crop production systems because of the increased risks of N losses from animal manures and the low availability of organically bound N to crops. A NUE higher than 60% risks inducing soil mining (i.e., N removal exceeds N input, declining soil fertility and plant yield), and a NUE below 20% is deemed too low (i.e., N inputs to the systems exceed total N demand), even accounting for the inherently low conversion efficiency of the animal feed protein-N in milk and meat protein-N.

The N surplus target value was not set because there is no information to relate it to the magnitude of actual losses of reactive N species to the environment, particularly water courses. As a tentative reference, we set ranges of N surplus from <80 to 100-160 to >160 kg N surplus ha^{-1}(9)(22). This is based on NUE results (see below): systems with N surplus below 80 kg N ha^{-1} could increase their NUE, but NUE would decrease for surpluses above 160 kg N ha^{-1}.

3. Results

3.1 Farm-gate balance

The farm-gate balance of the average Uruguayan dairy systems was similar in 2014 and 2019, as no major changes were observed in inputs, outputs, and surplus between the two surveys, although NUE did improve (**Table 2**, **Table S2** and **Table S5**). In these systems, inputs were similarly distributed between fertilizer, imported feeds and biological N fixation and N atmospheric deposition, which accounted for 32, 31 and 37% of total N inputs, respectively. Outputs were amply dominated by milk production, as live weight production made a minor contribution. The seven modal dairy farms identified in 2019 imported on average 103 kg N ha^{-1} (ranging from 59 to 137 kg N ha^{-1}) and exported 32 kg N ha^{-1} (ranging from 13 to 42 kg N ha^{-1}), thus presenting a N surplus of 71 kg N ha^{-1} (44 and 97 kg N ha^{-1}) (**Table 2**, **Table S5**).

There was a disparity between modal dairy farms (2019) in their contribution to the national dairy N surplus, depending on how their contribution is assessed. When considered in terms of produced milk, all modal systems contributed rather proportionally, and thus, the cumulative milk production scaled almost equally with cumulative N surplus (Gini coefficient = 0.21: **Figure 1**A). However, modal dairy systems differed greatly in size, and therefore just 21% of the number of farms (i.e., those grouped in the M5B, M5A and M6 modal systems) accounted for 74% of the total national dairy N surplus (Gini coefficient = 0.69; **Figure 1**B).

The farm-gate balance of the “CRS” and “10MIL” intensified systems had a N surplus 79 to 280% higher than the average 2019 modal dairy system, respectively (**Table 2**). In the “CRS” systems, NUE remained similar to the 2019 average dairy system, but NUE decreased to 22% in the “10MIL” systems. In the intensified systems, fertilizer and imported feeds became the main N inputs, accounting for 37 and 43% of total N inputs, respectively. Although intensification changed little absolute biological N fixation, this source became relatively less important.

Farm-gate N surplus increased with intensification (**Table 2**, **Figure 2** and **Figure 3**). Close positive relationships were observed between N surplus and N input (R^2=0.998) and N output (R^2=0.965). However, while N surplus increased proportionally more as N input increased (b=1.26; **Figure 2**A, **Figure 2**D), N output increased proportionally less (b=0.33; **Figure 2**B). Therefore, N surplus and N output had a markedly nonlinear link (b=2.14). As a direct consequence of these allometric relationships, NUE was not associated with N inputs in a simple way (R^2=0.00; **Figure 2**C). Instead, NUE showed a complex relationship with N inputs, increasing up to 100 kg N ha^{-1} and decreasing above 200 kg N ha^{-1}.

The link between N surplus and all indicators of intensification was also nonlinear. It increased at an accelerating rate as milk solids productivity increased (b=1.77; **Figure 3**A). This pattern was also clear for stocking rate (b=1.93), total feed intake (b=2.33), as well as for operating profit (b=1.42; **Figure 3**B-D). This means that increments in all these variables resulted in progressively more significant N surpluses.

Table 2. Farm-gate N balance of the national average dairy systems (2014 and 2019) and the "CRS" and "10MIL" intensified systems

	NATIONAL DAIRY SYSTEMS[1]				INTENSIFIED DAIRY SYSTEMS					
	2014		2019		"CRS"		"10MIL"			
Farm-gate N balance	Mean	SD	Mean	SD	CRS 1.5	CRS 2.0	GFix-NAHF	GFix-NZHF	GMax-NAHF	GMax-NZHF
N inputs (kg N ha^{-1})	105.4	27.6	103.2	26.8	174.1	199.4	352.3	390.6	326.5	354.1
Fertilizer	34.8	11.8	32.9	9.3	66.6	71.7	150.7	180.4	131.1	153.1
Imported feed	34.0	14.1	29.9	13.0	67.4	91.9	163.4	176.0	138.8	144.4
N fixation	29.3	5.3	33	6.2	32.8	28.5	30.9	26.8	49.3	49.2
Atmospheric deposition	7.3	0.0	7.3	0.0	7.3	7.3	7.3	7.3	7.3	7.3
Silage surplus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N outputs (kg N ha^{-1})	30.0	9.1	32	10.8	51.8	66.7	83.1	91.3	76.5	89.3
Milk	29.7	9.1	31.6	10.7	51.3	66.0	82.4	90.5	75.9	88.6
Livestock	0.4	0.1	0.4	0.2	0.5	0.7	0.7	0.8	0.6	0.7
N surplus (kg N ha^{-1})	75.4	18.9	71.2	16.6	122.3	132.7	269.2	299.3	250.1	264.8
NUE (%)	28.3	2.7	30.5	4.7	29.7	33.5	23.6	23.4	23.4	25.2

[1] The national average was calculated as the milk production-weighted of all modal dairy farm systems surveyed in 2014 and 2019.

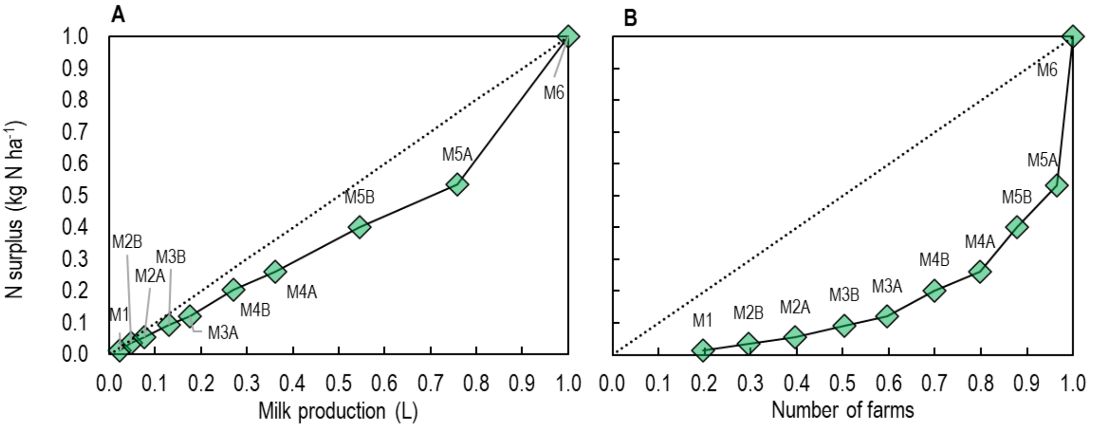

Figure 1. Gini plot of cumulative proportional total milk production (A) for total number of dairy farms *vs.* (B) cumulative proportional N surplus for Uruguayan modal dairy systems in 2019

The labels indicate each different modal system (see **Table S2**). The dotted line represents the 1:1 relationship.

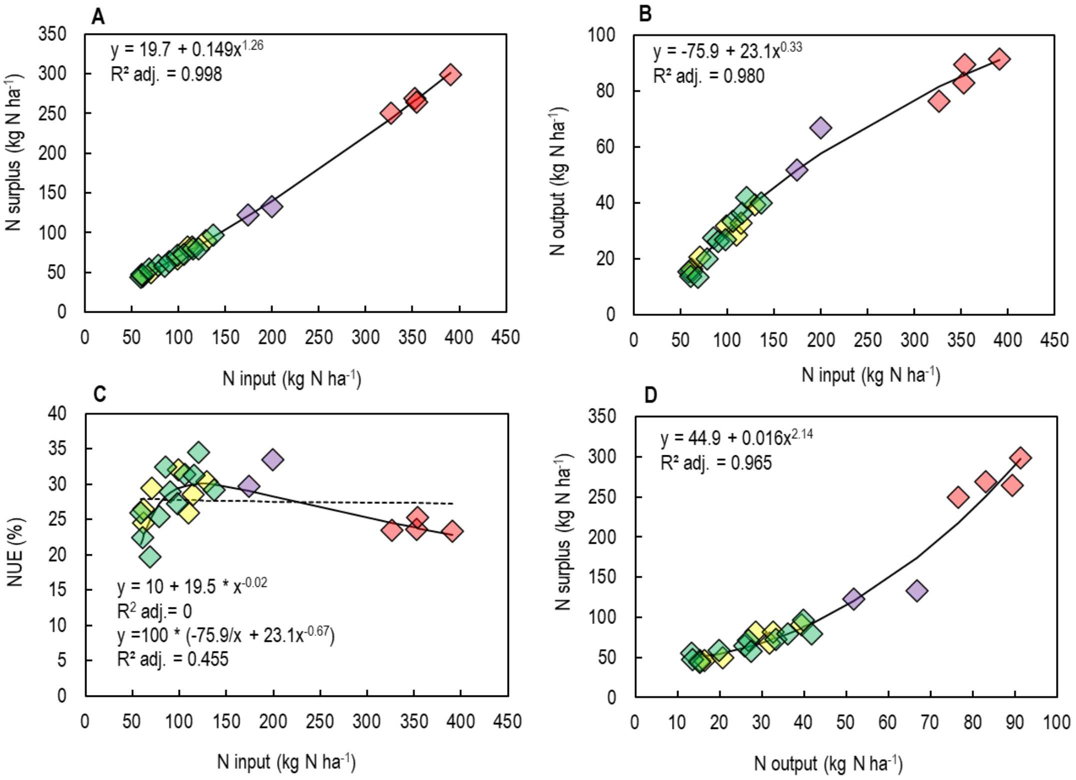

Figure 2. Relationships between the components of farm-gate balance: N input, N output, N surplus and N use efficiency (NUE)

Each data point is a dairy system (yellow, 2014 modal dairy systems; green, 2019 modal dairy systems; violet, “CRS” intensified systems, and red, “10MIL” intensified systems). Continuous lines are statistically significant regression models (p<0.01).

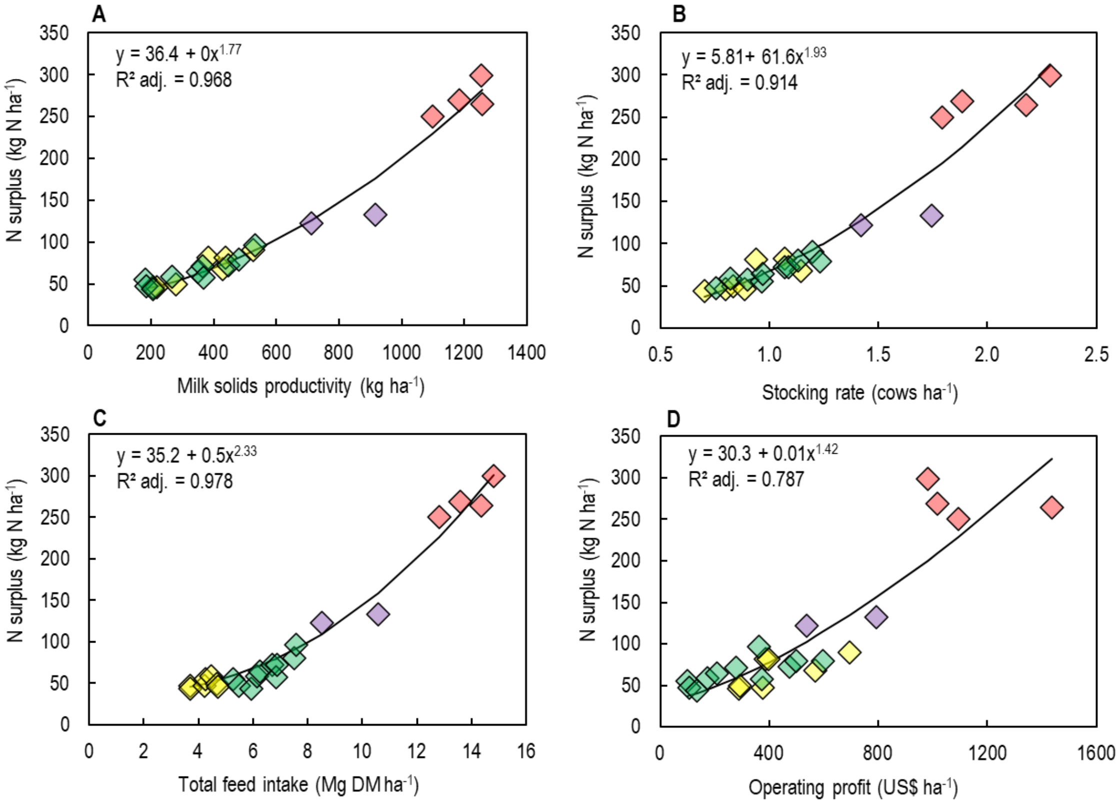

Figure 3. Relationships between N surplus and several parameters associated with intensification: milk solids productivity (A), stocking rate (B), total feed intake (C) and operating profit (D)

Each data point is a dairy system (yellow, 2014 modal dairy systems; green, 2019 modal dairy systems; violet, “CRS” intensified systems, and red, “10MIL” intensified systems). Continuous lines represent statistically significant regression models ($p<0.01$).

3.2 Mapping results onto the EU Nitrogen Expert Panel input-output framework

When the relationship between N inputs and outputs for each farm system evaluated was mapped onto the EU Nitrogen Expert Panel input-output framework, NUE and N output targets were achieved by some, but not all, assessed systems (**Figure 4**). On one hand, the most extensive modal systems had adequate NUE but too low N outputs (i.e., N output below the minimum required to be profitable; 19 and 21 kg N ha^{-1}). On the other hand, “10MIL” systems presented high N output and NUE within the desired range, but their N surplus was substantially greater than 160 kg N ha^{-1}. The same pattern was observed in pastoral dairy systems from New Zealand, Australia, Europe, and the US(2)(7)(9).

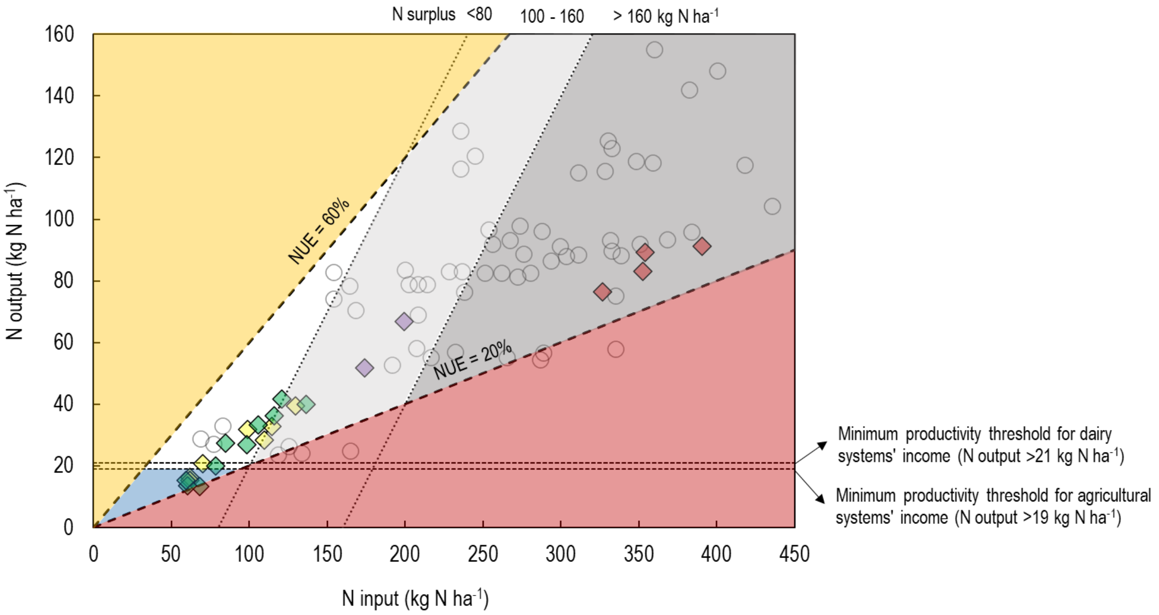

Figure 4. Annual N input and N output values of dairy systems mapped onto the framework proposed by the EU N Expert Panel(22). The two dashed lines encompass the 20-60% range of desired NUE, as lower values risk increasing N pollution and higher values risk mining soil N. The horizontal dotted lines represent the N output associated with the minimum productivity to reach an operating profitable to either (i) remunerate the land and capital factors for current Uruguayan dairy systems or (ii) equal the average operating profit of current agricultural systems that compete for land with dairy systems. Finally, the shaded grey gradient represents the current uncertainty regarding what N surplus would lead to substantial losses of harmful reactive N species.

Each data point is a dairy system (yellow, 2014 modal dairy systems; green, 2019 modal dairy systems; violet, “CRS” intensified systems; red, “10MIL” intensified systems; non-coloured, de Klein and others(9)).

4. Discussion

This study amalgamated data from the 2014 and 2019 national surveys of current commercial dairy farms with data from simulated systems adopting intensification strategies based on the outcomes of experimental research farmlets. This unique database of farm-gate N balances of dairy systems constitutes the first assessment of the overall current national dairy situation and the impact of prospective intensified systems.

4.1 Current and future dairy farming systems: the impact of intensification

Current pastoral dairy systems in Uruguay have lower stocking rates and productivity than pasture-based dairy systems from New Zealand, Australia, Northern Europe, or the US (*c.f.* **Table 1** *vs.* McDowell and others(29); Luo & Ledgard(30); Ros and others(31)). Likewise, the N surplus of current Uruguayan dairy systems, at 71 kg N ha^{-1}, is at the lower end of the values reported for pastoral dairy systems worldwide(9), less than half the national average dairy N surplus of New Zealand(30) (186-281 kg N ha^{-1}), Australia(32) (156 kg N ha^{-1}), Ireland(33) (155 kg N ha^{-1}), or the Netherlands(34) (174-208kg N ha^{-1}). However, the NUE of current Uruguayan dairy farms (20-35%) is within the 20-40% range reported for dairy systems worldwide(9). Therefore, the performance of the Uruguayan dairy in terms of farm-gate N balance, as measured in 2019, is relatively better than comparable systems. Furthermore, NUE increased by two per cent points between 2014 and 2019 (**Table 1**).

Intensification of pastoral dairying in Uruguay, *via* enhanced forage consumption and increased stocking rate, has been shown to improve profitability in commercial(11) and experimental dairy farms(16)(17). For instance, the intensified "CRS" and "10MIL" systems achieved two- to three-fold rises in operating profit compared to the national dairy systems. However, economic performance alone does not guarantee the sustainable intensification of dairy(1)(35). Increasing milk production per hectare while maintaining low production costs to remain internationally competitive may entail greater environmental risks.

Farm-gate N balance shows that the "CRS" and "10MIL" intensified systems imported on average 187 and 356 kg N ha^{-1} and exported 59 and 85 kg N ha^{-1}. This resulted in an average N surplus of 128 and 271 kg N ha^{-1}, respectively (**Table 2**, **Figure 4**), comparable to those of intensified pasture-based dairy systems in leading exporting countries(29)(30)(31).

These results confirm the general trend reported in the literature that intensification of dairy systems increases stocking rate, milk production and operating profit, but also farm-gate N surplus(2)(7)(9)(22)(36). Therefore, it is safe to assume that environmental problems associated with intensified dairy systems in more developed countries may also emerge at some stage due to intensification in Uruguay.

As the average dairy farm intensifies by adopting "CRS" and "10MIL" strategies, N inputs to the farm system increased due to higher use of fertilizer and imported feeds required to support larger feed demand of higher stocking rates. Notably, the NUE of the intensified systems was neither consistently lower nor related to the composition of N inputs. Opposite to negative trends observed in other countries(9), in the present study, NUE peaked at intermediate values of N input, a consequence of the shape of the allometric relationship between N outputs and inputs (**Figure 2**C).

4.2 Mapping Uruguayan dairy farms onto the EU Nitrogen Expert Panel framework

Optimal N performance targets would ideally combine the efficient use of high N inputs to sustain animal productivity while minimising N loss(9). Plotting systems in terms of their N input and output allows us to assess their compliance (or not) with three concurrent targets(22). First, a N output target is defined by the minimum profitability required to be competitive (e.g., against other land uses). Second, NUE targets set by achievable efficiency under local agroecological conditions. Third, a maximum N surplus target to avoid losses to the environment of harmful reactive N species. This is the most uncertain target and should be defined for the specific conditions according to environmental sensitivity and policy(37).

Mapping Uruguayan farms in the N input-output framework shows that current dairy systems present a lower N surplus than intensified systems, and, thus, less potential risk of harmful N losses. However, 40% of these systems (i.e., M1, M2B, M3B, M4B), which account for 20% of national milk production, had N outputs below the minimum 21 kg N ha^{-1} required to be competitive in Uruguay (**Figure 4**). Notably, de Klein and others(9) placed that threshold at 80 kg N ha^{-1} for other pastoral countries, perhaps due to higher values of land.

At the other end of the distribution, the most intensified systems presented the highest output per hectare and NUE above 20%, but also the highest N surplus. Finally, some current and intensified systems plot in the space comprising the desirable range of outcomes for all targets. This suggests that intensified dairy systems can, in fact, be more profitable than the current average system while complying with N performance targets.

4.3 Strategies for sustainable intensification

Different strategies can improve N performance. These strategies can be grouped into intensification, extensification, increasing efficiency and avoiding soil degradation(22) (**Figure S2**). Our results suggest that, in Uruguay, dairy farms with low productivity could increase N inputs and improve their performance without major increases in risk of environmental impact. These systems —which comprised 50% of dairy farms in 2019— could reach the desirable range of outcomes (unshaded part of the figure) following a "traditional" intensification pathway.

For the most intensified and profitable systems (e.g., “10MIL”), the challenge is to increase their efficiency (i.e., NUE) and reduce N surplus. This requires improving, first, internal N recycling, especially N in animal excreta(9), to reduce fertilizer inputs, and second, the amount of harvested grass per unit of N fertilizer applied(38). These adjustments allow either greater N output in saleable products for the same N input, or lower N inputs while maintaining N outputs.

Provided appropriate management practices are adopted to account for those two key aspects, intensified pasture-based dairy may be achieved without major increases in N surplus. In the Netherlands, N surplus remained unchanged in commercial dairy farms between 2013 and 2015 due to the implementation of environmental regulations limiting N application and making mandatory the export of manure surpluses(34). Similarly, intensified Irish dairy farms reported positive impacts of regulations upon N surplus and NUE due to less inorganic fertilizer N use and improved manure application timing(39).

4.4 Need for further research

Farm-gate N balances are the simplest indicator of a dairy farm’s environmental performance. Its simplicity, however, is also its main drawback because N surplus is not linearly or unequivocally related to harmful N losses to the environment, i.e. nitrate leaching or ammonia volatilisation(4)(40)(41)(42)(43). Indeed, the relationship between N balances and groundwater concentrations has been found to be poor, unclear, or non-existent(4)(40)(43). Moreover, part of the N surplus might not be lost to the environment but stored in soil organic matter, bringing both environmental and productive benefits(44). Therefore, N surplus is best interpreted as an indicator of *potential* risk(2)(9).

Pollution from reactive N is arguably the planetary boundary surpassed to a larger extent by food production systems(45). Whether the high N surplus associated with intensive dairy systems would end up increasing water pollution —the most problematic local impact of N excess— requires research. Future studies, possibly combining field measurements with simulation models, should quantitatively assess the relationship between N surplus and the biochemical identity, spatial distribution, and temporal dynamics of N losses. Without this, there is no solid basis for designing either (i) effective N management options for the spatial and temporal hotspots that contribute disproportionally to N environmental risk, or (ii) sound targeted policies able to optimise the compromise between economic and environmental sustainability of dairy systems.

5. Conclusions

This study consolidates data on the N balance of current dairy systems in Uruguay and offers insights into the potential effects of intensification. First, current dairy systems in Uruguay present a comparatively low N surplus compared to other pasture-based systems worldwide, but at the same time, many of those current systems have N outputs that compromise their economic sustainability. Second, the intensification of dairy systems achieving higher profits entails increases in farm-gate N surplus. The pronounced nonlinearity observed in the surplus-intensification relationship is particularly concerning.

The insights gleaned from this study may help guide technological advancements and policy formulation, fostering innovative and sustainable farming practices that contribute to achieving a more environmentally responsible and economically robust dairy sector. Specifically, we deem it essential that future research assess the fate of N surplus, i.e., its partitioning into the various N loss pathways, which carry quite different environmental consequences, and accumulation in soil organic matter, which carries environmental and productive benefits. Finally, the large inequality in the contribution of individual modal dairy systems to the national N surplus can be considered if effective policy is sought after.

Acknowledgements

This work was funded by the National Institute of Agriculture Research (INIA). The authors acknowledge the dairy farm staff and students for their assistance during the farmlet trials at INIA La Estanzuela and CRS Faculty of Agronomy. FL and FAL were financially supported by PROCISUR and FONTAGRO through the project “Uso de leguminosas en sistemas ganaderos sudamericanos”.

Transparency of data

The entire data set that supports the results of this study was published in the article itself.

Author contribution statement

SS: Conceptualization; Data curation; Formal analysis; Investigation; Writing - original draft
FL: Data curation; Writing – review & editing
GO: Data curation; Writing – review & editing
ALM: Data curation
AP: Data curation; Writing – review & editing
JA: Data curation; Writing – review & editing
GG: Data curation
SF: Conceptualization; Writing – review & editing
PC: Conceptualization; Writing – review & editing
FAL: Conceptualization; Supervision; Writing – review & editing

References

(1) Clay N, Garnett T, Lorimer J. Dairy intensification: Drivers, impacts and alternatives. Ambio. 2020;49(1):35-48. Doi: 10.1007/s13280-019-01177-y.

(2) Powell JM, Gourley CJP, Rotz CA, Weaver DM. Nitrogen use efficiency: A potential performance indicator and policy tool for dairy farms. Environ Sci Policy. 2010;13(3):217-28. Doi: 10.1016/j.envsci.2010.03.007.

(3) Cameron KC, Di HJ, Moir JL. Nitrogen losses from the soil/plant system: a review. Ann Appl Biol. 2013;162(2):145-73. Doi: 10.1111/aab.12014.

(4) Beukes PC, Scarsbrook MR, Gregorini P, Romera AJ, Clark DA, Catto W. The relationship between milk production and farm-gate nitrogen surplus for the Waikato region, New Zealand. J Environ Manage. 2012;93(1):44-51. Doi: 10.1016/j.jenvman.2011.08.013.

(5) Gourley CJP, Dougherty WJ, Weaver DM, Aarons SR, Awty IM, Gibson DM, Hannah MC, Smith AP, Peverill KI. Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms. Anim Prod Sci. 2012;52(10):929-44. Doi: 10.1071/AN11337.

(6) Oenema J, Oenema O. Unraveling feed and nutrient use effciencies in grassland based dairy farms. Front Sustain Food Syst. 2022;6:846561. Doi: 10.3389/fsufs.2022.846561.

(7) Treacy M, Humphreys J, Namara KM, Browne R, Teagasc CJW. Farm-gate nitrogen balances on intensive dairy farms in the south west of Ireland. Ir J Agric Food Res. 2008;47:105-17.

(8) Clark DA, Caradus JR, Monaghan RM, Sharp P, Thorrold BS. Issues and options for future dairy farming in New Zealand. J Agric Res. 2007;50(2):203-21. Doi: 10.1080/00288230709510291.

(9) de Klein CAM, Monaghan RM, Ledgard SF, Shepherd M. A system's perspective on the effectiveness of measures to mitigate the environmental impacts of nitrogen losses from pastoral dairy farming. In: Proceedings of the 4th Australasian Dairy Science Symposium. Canterbury: Lincoln University; 2010. p. 14-28.

(10) Dillon P, Shalloo L, Murphy D, O'Brien D, Richards K, O'Donovan M, Ruelle E. The impact of nitrogen management strategies within grass based dairy systems [Internet]. Oak Park: Teagasc; 2021 [cited 2024 Feb 29]. 49p. Available from: https://www.teagasc.ie/publications/2021/the-impact-of-nitrogen-management-strategies-within-grass-based-dairy-systems.php.

(11) Fariña SR, Chilibroste P. Opportunities and challenges for the growth of milk production from pasture: the case of farm systems in Uruguay. Agric Syst. 2019;176:102631. Doi: 10.1016/j.agsy.2019.05.001.

(12) Chilibroste P. A major challenge for the Uruguayan dairy industry: sustainable growth. Agrocienc Urug. 2021;25(2):e970. Doi: 10.31285/AGRO.25.970.

(13) Ministerio de Ganadería, Agricultura y Pesca, DIEA (UY). Anuario estadístico agropecuario 2020 [Internet]. Montevideo: MGAP; 2020 [cited 2024 Feb 29]. Available from: https://bit.ly/3UXE8s6

(14) OECD; FAO. OECD-FAO agricultural outlook 2021-2030. Paris: OECD Publishing; 2021. 337p. Doi: 10.1787/19428846-en.

(15) Ortega G, Nuñez T, Custodio D, Mello R, López Y, Chilibroste P. Effect of stocking rate on pasture production and utilisation on a grazing dairy system during winter and spring. In: Abstracts of the 2018 American Dairy Science Association Annual meeting. Knoxville: American Dairy Science Association; 2018. p. 257.

(16) Stirling S, Delaby L, Mendoza A, Fariña S. Intensification strategies for temperate hot-summer grazing dairy systems in South America: effects of feeding strategy and cow genotype. J Dairy Sci. 2021;104(12):12647-63. Doi: 10.3168/jds.2021-20507.

(17) Stirling S. Estrategias de intensificación para sistemas lecheros pastoriles en Uruguay: análisis biofísico y del potencial impacto ambiental [doctoral's thesis]. Montevideo (UY): Universidad de la República, Facultad de Veterinaria; 2022. 155p.

(18) Darré E, Llanos E, Astigarraga L, Cadenazzi M, Picasso V. Do pasture-based mixed dairy systems with higher milk production have lower environmental impacts? A Uruguayan case study. J Agric Res. 2021;64(3):444-62. Doi: 10.1080/00288233.2020.1750433.

(19) INALE. Encuesta 2014: resultados definitivos agrupados [Internet]. Montevideo: INALE; 2019 [cited 2024 Feb 29]. Available from: https://www.inale.org/estadisticas/encuesta-2014-resultados-definitivos-agrupados/

(20) INALE. Encuesta Lechera 2019: resultados definitivos [Internet]. Montevideo: INALE; 2021 [cited 2024 Feb 29]. Available from: https://www.inale.org/estadisticas/encuesta-lechera-2019-resultados-definitivos/

(21) Ortega G, Chilibroste P, Garrido JM, Waller A, Fariña SR, Lattanzi FA. Monitoring herbage mass and pasture growth rate of large grazing areas: a comparison of the correspondence, cost and reliability of indirect methods. J Agric Sci. 2023;161:502-11. Doi: 10.1017/S0021859623000333.

(22) EU Nitrogen Expert Panel. Nitrogen use efficiency (NUE) an indicator for the utilization of nitrogen in agriculture and foodsystems. Wageningen: Wageningen University; 2015. 47p.

(23) Mcdonald P, Edwards RA, Greenhalgh JFD, Morgan CA. Animal nutrition. Englewood Cliffs: Prentice Hall; 1995. 696p.

(24) Lussich F. Variabilidad de la fijación biológica de nitrógeno de leguminosas forrajeras en Uruguay: posibles causas y consecuencias nutricionales [master's thesis]. Montevideo (UY): Universidad de la República, Facultad de Agronomía; 2020. 102p.

(25) Carnelos DA, Portela SI, Jobbágy EG, Jackson RB, Di Bella CM, Panario D, Fagúndez C, Piñeiro-Guerra JM, Grion L, Piñeiro G. A first record of bulk atmospheric deposition patterns of major ions in southern South America. Biogeochemistry. 2019;144(3):261-71. Doi: 10.1007/s10533-019-00584-3.

(26) Agricultural Research Council. The nutrient requirements of ruminant livestock. Oxon: CAB International; 1994. 351p.

(27) Gini C. Measurement of inequality of incomes. Econ J. 1921;31(121):124-6. Doi: 10.2307/2223319.

(28) Brentrup F, Pallière C. Nitrogen use efficiency as an agro-environmental indicator. In: Proceedings of the OECD workshop on OECD agri-environmental indicators: lessons learned and future directions, 23-26 March, 2010. Leysin: OECD; 2010. p. 23-6.

(29) McDowell RW, Rotz CA, Oenema J, Macintosh KA. Limiting grazing periods combined with proper housing can reduce nutrient losses from dairy systems. Nat Food. 2022;3(12):1065-74. Doi: 10.1038/s43016-022-00644-2.

(30) Luo J, Ledgard S. New Zealand dairy farm systems and key environmental effects. Front Agric Sci Eng. 2021;8(1):148-58. Doi: 10.15302/J-FASE-2020372.

(31) Ros MBH, Godber OF, Olivo AJ, Reed KF, Ketterings QM. Key nitrogen and phosphorus performance indicators derived from farm-gate mass balances on dairies. J Dairy Sci. 2023;106(5):3268-86. Doi: 10.3168/jds.2022-22297.

(32) Stott KJ, Gourley CJP. Intensification, nitrogen use and recovery in grazing-based dairy systems. Agric Syst. 2016;144:101-12. Doi: 10.1016/j.agsy.2016.01.003.

(33) Buckley C, Wall DP, Moran B, O'Neill S, Murphy PNC. Farm gate level nitrogen balance and use efficiency changes post implementation of the EU nitrates Directive. Nutr Cycl Agroecosystems. 2016;104(1):1-13. Doi: 10.1007/s10705-015-9753-y.

(34) Oenema J, Oenema O. Intensification of grassland-based dairy production and its impacts on land, nitrogen and phosphorus use efficiencies. Front Agric Sci Eng. 2021;8(1):130-47. Doi: 10.15302/J-FASE-2020376.

(35) Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HC. Agriculture: Sustainable intensification in agriculture: premises and policies. Science. 2013;341(6141):33-4. Doi: 10.1126/science.1234485.

(36) Haas G, Deittert C, Köpke U. Farm-gate nutrient balance assessment of organic dairy farms at different intensity levels in Germany. Renew Agric Food Syst. 2007;22(3):223-32. Doi: 10.1017/S1742170507001780.

(37) Quemada M, Lassaletta L, Jensen LS, Godinot O, Brentrup F, Buckley C, Foray S, Hvid SK, Oenema J, Richards KG, Oenema O. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agric Syst. 2020;177:102689. Doi: 10.1016/j.agsy.2019.102689.

(38) Rawnsley RP, Smith AP, Christie KM, Harrison MT, Eckard RJ. Current and future direction of nitrogen fertiliser use in Australian grazing systems. Crop Pasture Sci. 2019;70(12):1034-43. Doi: 10.1071/CP18566.

(39) Mihailescu E, Murphy PNC, Ryan W, Casey IA, Humphreys J. Nitrogen balance and use efficiency on twenty-one intensive grass-based dairy farms in the South of Ireland. J Agric Sci. 2014;152(5):843-59. Doi: 10.1017/S0021859614000045.

(40) Humphreys J, O'Connell K, Casey IA. Nitrogen flows and balances in four grassland-based systems of dairy production on a clay-loam soil in a moist temperate climate. Grass Forage Sci. 2008;63(4):467-80. Doi: 10.1111/j.1365-2494.2008.00660.x.

(41) Pinxterhuis JB, Beare MH, Edwards GR, Collins RP, Dillon P, Oenema J. Eco-efficient pasture based dairy farm systems: a comparison of New Zealand, The Netherlands and Ireland. In: Grassland and forages in high output dairy farming systems. Wageningen: Grassland Science in Europe; 2015. p. 349-66.

(42) Hoekstra NJ, Schulte RPO, Forrestal PJ, Hennessy D, Krol DJ, Lanigan GJ, Müller C, Shalloo L, Wall DP, Richards KG. Scenarios to limit environmental nitrogen losses from dairy expansion. Sci Total Environ. 2020;707:134606. Doi: 10.1016/j.scitotenv.2019.134606.

(43) Burchill W, Lanigan GJ, Li D, Williams M, Humphreys J. A system N balance for a pasture-based system of dairy production under moist maritime climatic conditions. Agric Ecosyst Environ. 2016;220:202-10. Doi: 10.1016/j.agee.2015.12.022.

(44) Soussana JF, Lemaire G. Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. Agric Ecosyst Environ. 2014;190:9-17. Doi: 10.1016/j.agee.2013.10.012.

(45) Leip A, Bodirsky BL, Kugelberg S. The role of nitrogen in achieving sustainable food systems for healthy diets. Glob Food Sec. 2021;28:100408. Doi: 10.1016/j.gfs.2020.100408.

(46) Ledgard SF, Steele KW. Biological nitrogen fixation in mixed legume/grass pastures. Plant and Soil. 1992;141:137-53. Doi: 10.1007/BF00011314.

Supplementary material

Table S1. Farm systems description of the 2014 Modal dairy systems (ML1, ML2, ML4, ML6, ML8, ML10, ML12) and the milk-, area- and farm-weighted average

	2014 MODAL DAIRY SYSTEMS							Milk-weighted average	Area-weighted average	Farm-weighted average
	ML1	ML2	ML4	ML6	ML8	ML10	ML12			
Representativity										
Milk	3%	7%	10%	11%	12%	30%	27%			
Area	4%	12%	8%	13%	10%	31%	21%			
Farms	20%	19%	21%	11%	12%	8%	8%			
Systems description										
Milk production (L)	92,507	262,333	315,003	666,246	706,836	2,517,695	2,168,103	1,544,087	1,470,126	678,953
Farm area (ha)	32	95	55	178	120	491	306	276	272	136
Milking cows	20	55	47	110	104	354	296	219	210	103
Total cows	28	76	63	149	129	460	367	280	270	133
Milking: total cows	0.71	0.72	0.75	0.74	0.81	0.77	0.81	0.77	0.77	0.75
Stocking rate (cows ha^{-1})	0.88	0.80	1.15	0.84	1.07	0.94	1.20	1.02	0.99	0.97
Milk productivity (L ha^{-1})	2,922	2,759	5,776	3,736	5,896	5,132	7,078	5,417	5,117	4,458
Milk solids (kg MS ha^{-1})	217	205	430	278	439	382	527	403	381	332
Land use (%)										
Mix pastures	52	54	55	63	51	54	51	54	54	54
Annual pastures/crops	41	39	36	26	34	32	26	31	32	35
Crops	7	8	9	11	14	14	15	13	13	10
Feed intake (Mg DM ha^{-1})										
Concentrates	0.5	0.8	1.2	0.9	1.6	1.9	2.1	1.6	1.5	1.1
Silage	1.3	1.2	1.9	1.4	1.9	2.2	1.9	1.9	1.8	1.6
Pasture	2.8	2.3	3.8	2.4	3.3	2.0	3.9	3.0	2.8	3.0
Bought-in concentrate (%)	84	70	83	79	80	86	84	82	82	80
Bought-in silage (%)	15	2	16	2	11	0	5	5	5	9
Operating profit (US$ ha^{-1})	288	376	570	291	386	397	694	476	451	419

Table S2. Farm systems description of the 2019 Modal dairy systems (M1, M2B, M2A, M3B, M3A, M4B, M4A, M5B, M5A, M6) and the milk-, area- and farm-weighted average

	2019 MODAL DAIRY SYSTEMS										Milk-weighted average	Area-weighted average	Farm-weighted average
	M1	M2B	M2A	M3B	M3A	M4B	M4A	M5B	M5A	M6			
Representativity													
Milk	2%	3%	3%	5%	5%	10%	9%	18%	21%	24%			
Area	3%	3%	8%	4%	15%	6%	11%	12%	20%	18%			
Farms	4%	4%	12%	5%	18%	6%	14%	9%	17%	12%			
Systems description													
Milk production (L)	83,492	191,569	206,855	371,882	362,679	696,181	682,031	1,686,827	1,828,024	4,965,120	2,075,791	1,651,745	1,308,863
Farm area (ha)	34	78	43	135	61	195	96	351	248	792	350	275	220
Milking cows	23	44	35	67	51	120	95	238	234	682	287	228	182
Total cows	33	59	47	95	65	160	120	315	306	897	377	300	239
Milking: total cows	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Stocking rate (cows ha^{-1})	1.0	0.8	1.1	0.7	1.1	0.8	1.2	0.9	1.2	1.1	1.1	1.1	1.1
Milk productivity (L ha^{-1})	2,441	2,447	4,792	2,756	5,961	3,572	7,069	4,812	7,360	6,272	5,625	5,670	5,551
Milk solids (kg MS ha^{-1})	182	186	364	207	448	268	534	368	555	480	427	429	420
Land use (%)													
Mix pastures	59	64	53	60	60	62	55	65	57	65	61	60	59
Annual pastures/crops	35	27	33	30	36	30	36	26	30	26	29	31	31
Crops	6	9	15	11	4	8	8	9	13	9	10	10	9
Feed intake (Mg DM ha^{-1})													
Concentrates	0.6	0.6	1.0	0.7	1.2	0.9	1.5	1.1	2.0	1.8	1.4	1.4	1.3
Silage	1.1	0.8	1.5	0.7	1.2	0.8	1.5	1.2	1.8	1.5	1.3	1.4	1.3
Pasture	2.6	2.4	3.4	2.3	3.9	2.8	4.5	3.0	3.8	3.4	3.4	3.5	3.5
Bought-in concentrate (%)	90	81	73	75	100	80	100	94	95	95	92	92	91
Bought-in silage (%)	12	3	29	4	31	6	7	5	4	4	7	11	13
Operating profit (US$ ha^{-1})	101	108	278	135	475	174	362	372	598	498	407	406	385

Supplement S3. Estimation of N input *via* biological N_2 fixation by forage legumes

To estimate N input *via* biological N_2 fixation, we assumed, first, that legumes accounted for 40% of consumed DM (including pasture grazed and harvested for reserves), and second, that 36.5 kg of N were fixed for each Mg of consumed legume DM.

Assumption 1. We simulated the average proportion of legume DM for three frequent sequences in dairy systems of Uruguay (based on information from INALE(19)). These comprised annual winter forage crops (VI, pure grass, typically ryegrass or oats), mixed perennial pastures (PP, grass/legume) and annual summer forage crops (VV, pure grass, typically sudangrass). The main differences between sequences are the botanical composition and length of the phase with perennial pasture: 3.5 years for alfalfa+dactylis and for tall fescue+white clover/*lotus corninulatus* mixtures, and 1.5 years for red clover+ryegrass/bromus mixtures. For longer pastures, we simulated evolutions with either high or low legume content. The average proportion of legumes across years and sequences ranged between 31 and 46%. We used 40% as a simplifying factor.

Proportion of legumes in consumed DM						
	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	**Average**
alfalfa + dactylis	VI	PP	PP	PP	PP / VV	
low legume content	0.00	0.80	0.65	0.40	0.10	0.39
high legume content	0.00	0.80	0.70	0.60	0.20	0.46
tall fescue + white clover/lotus	VI	PP	PP	PP	PP / VV	
low legume content	0.00	0.70	0.50	0.30	0.05	0.31
high legume content	0.00	0.70	0.65	0.50	0.15	0.40
red clover + ryegrass/bromus	VI	PP	PP / VV			
	0.00	0.70	0.50			0.40
Average Low legume content						0.38
Average High legume content						0.44

Assumption 2. We estimated the amount of N fixed per Mg of consumed DM for the three most frequent legume species in dairy farms in Uruguay: alfalfa, white clover and red clover (based on information from INALE(19)), assuming a 60-20-20 contribution, respectively. Data for the amount of N fixed per unit shoot DM for each species was taken from Lussich(24). This coefficient was then affected by an estimated proportion of consumed shoot DM, an estimated allocation of N to belowground organs(46), and an estimated recycling factor of N from senescent leaves so that Kg N fix/Mg DM consumed = kg N fix/Mg produced DM: consumed DM/produced DM × (1+allocation of N belowground) × adjustment N mobilisation.

Kg N fixed / Mg consumed DM				
	60%	20%	20%	
	Alfalfa	White clover	Red clover	**Average**
kg Nfix shoot/Mg DM shoot	22.0	26.0	27.0	
consumed DM/produced DM	65%	65%	65%	
allocation of N belowground	0.15	0.20	0.20	
adjustment for N mobilization	0.85	0.85	0.85	
kg Nfix/Mg consumed DM	33.1	40.8	42.4	36.5

Table S4. Farm-gate N balance of the 2014 modal dairy systems (ML1, ML2, ML4, ML6, ML8, ML10, ML12) and the milk-, area- and farm-weighted average

	2014 MODAL DAIRY SYSTEMS							Milk-weighted average	Area-weighted average	Farm-weighted average
Farm-gate N balance	ML1	ML2	ML4	ML6	ML8	ML10	ML12			
N inputs (kg N ha^{-1})	62.0	61.8	99.2	70.2	114.6	109.9	129.6	105.4	100.8	86.4
Fertilizer	15.5	20.5	29.6	19.1	40.7	34.8	46.6	34.8	32.9	27.0
Imported feed	12.6	10.3	25.1	15.6	34.2	44.5	42.0	34.0	32.2	22.7
N fixation	26.6	23.7	37.1	28.2	32.5	23.3	33.8	29.3	28.4	29.5
Atmospheric deposition	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
Silage surplus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N outputs (kg N ha^{-1})	16.4	15.2	31.7	20.6	32.7	28.4	39.4	30.0	28.4	24.7
Milk	15.9	15.0	31.4	20.3	32.4	28.2	38.9	29.7	28.0	24.3
Livestock	0.5	0.2	0.3	0.4	0.4	0.3	0.5	0.4	0.3	0.4
N surplus (kg N ha^{-1})	45.6	46.6	67.4	49.5	81.9	81.4	90.2	75.4	72.4	61.8
NUE (%)	26.4	24.6	32.0	29.4	28.6	25.9	30.4	28.3	27.9	28.1

Table S5. Farm-gate N balance of the 2019 Modal dairy systems (M1, M2B, M2A, M3B, M3A, M4B, M4A, M5B, M5A, M6) and the milk-, area- and farm-weighted average

	2019 MODAL DAIRY SYSTEMS										Milk-weighted average	Area-weighted average	Farm-weighted average
Farm-gate N balance	M1	M2B	M2A	M3B	M3A	M4B	M4A	M5B	M5A	M6			
N inputs (kg N ha^{-1})	68.2	60.5	98.4	59.2	105.8	78.6	136.6	84.8	120.9	115.9	103.2	104.5	103.7
Fertilizer	21.5	22.1	38.7	19.9	30.6	28.6	50.6	29.1	36.5	32.7	32.9	33.6	34.0
Imported feed	13.3	8.2	22.4	10.6	31.1	13.9	38.8	18.1	42.8	39.1	29.9	30.1	29.2
N fixation	26.2	22.9	30.0	21.5	36.8	28.8	40.0	30.4	34.4	36.8	33.0	33.4	33.2
Atmospheric deposition	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
Silage surplus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N outputs (kg N ha^{-1})	13.4	13.6	26.8	15.4	33.3	19.9	39.9	27.5	41.8	36.2	32.0	32.1	31.3
Milk	13.3	13.5	26.7	15.2	33.0	19.8	39.4	27.1	41.3	35.6	31.6	31.8	31.0
Livestock	0.2	0.1	0.1	0.2	0.2	0.2	0.5	0.4	0.4	0.5	0.4	0.3	0.3
N surplus (kg N ha^{-1})	54.8	46.9	71.6	43.8	72.5	58.6	96.7	57.4	79.1	79.7	71.2	72.4	72.3
NUE (%)	19.7	22.5	27.2	26.0	31.4	25.4	29.2	32.4	34.5	31.2	30.5	30.3	29.7

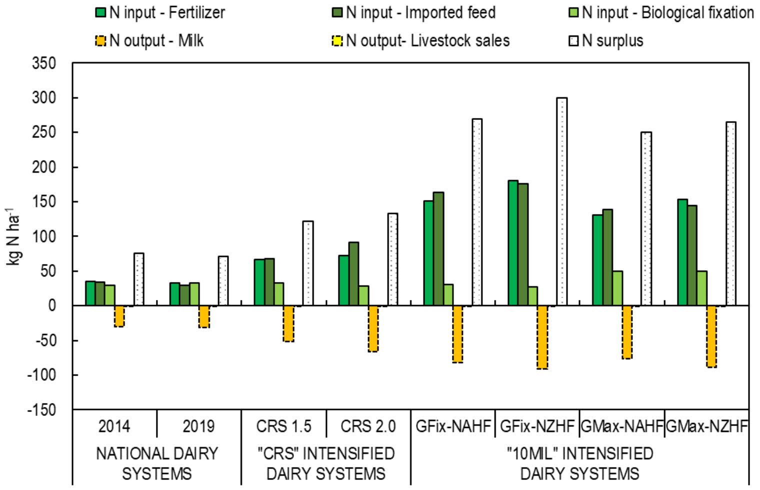

Figure S1. Farm-gate N balance of the 2014 and 2019 national average dairy systems and the “CRS” and “10MIL” intensified systems

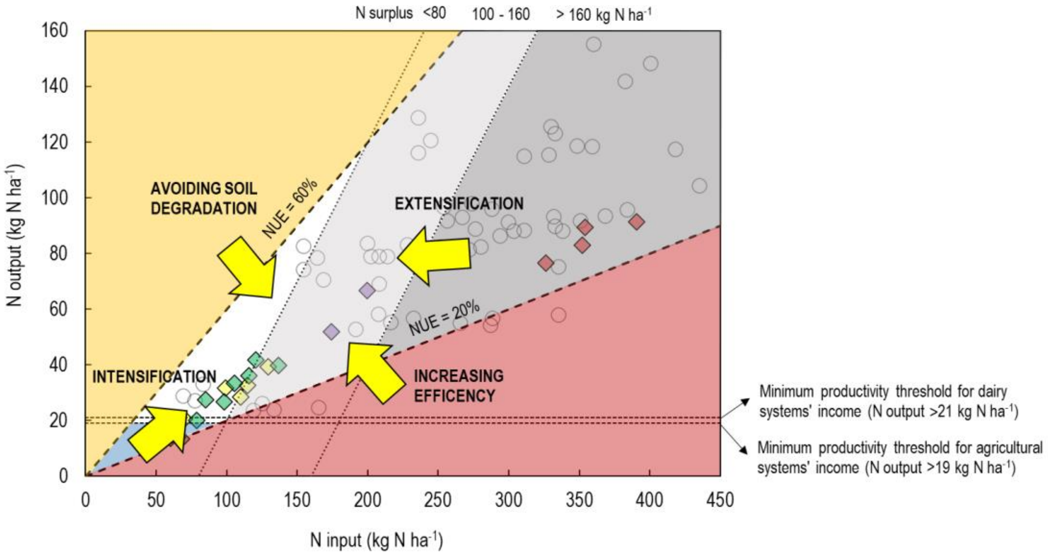

Figure S2. Ideal pathways that any farm could follow to enter the characteristic operating space (unshaded area): Intensification, extensification, increasing efficiency and avoiding soil degradation within the N input - N output framework proposed by the EU N Expert Panel[(22)]

Each data point is a dairy system (yellow, 2014 modal dairy systems; green, 2019 modal dairy systems; violet, “CRS” intensified systems; red, “10MIL” intensified systems; non-coloured, de Klein and others[(9)]).