Feed Substitution for adopting mitigation measures to reduce N_2O Emission in Irish Dairy and Cattle Farming

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Abstract

This paper aims to estimate the capacity to substitute concentrate feed for home-produced feed by adopting two specific mitigation strategies to reduce Nitrous Oxide (N_2O) emissions in the agriculture sector: (i) Low Emissions Slurry Spreading (LESS) and (ii) applying protected urea instead of CAN fertiliser. A translog cost function is estimated to obtain the price and cross-price elasticities of demand for concentrate and home-produced feed. To achieve our aim, we use the Teagasc National Farm Survey (NFS) from 2014 to 2021, which contains detailed information on agricultural activity. Furthermore, farms are categorised into four groups based on their environmental characteristics to show how environmental conditions influence farmers' decision-making processes. Our results show a marginal change in the purchase of concentrates due to adopting the two mitigation measures analysed, which is reflected in an increase in cross-price elasticity. However, these results are conditioned to the biophysical conditions of the farm soils.

Keywords: Feed substitution, Price and Cross-Price Elasticity, Mitigation Measures, N_2O Emissions.

1. Introduction

Ireland's total GHGs were 60.76 Mt CO_2 eq. in 2022 (excluding LULUCF) (Duffy et al., 2023). Meanwhile, the GHGs from the agriculture sector were 23.33 Mt CO2eq, representing 38.4% of the total GHGs. N_2O emissions contributed 22.8% to agriculture's GHGs, and the agriculture sector contributed 92.9% of total N_2O in the country. In recent years, agriculture N_2O emissions have only reduced by 1.1% compared with 1990 levels (Duffy et al., 2023). The Climate Action Strategy set a target of a 25% reduction in greenhouse gas emissions (5.75 Mt CO2 eq.) by 2030 for the sector, with the ultimate aim the carbon neutrality by 2050 (GI, 2022). However, the world also faces food and nutrition crises, and mitigation actions must deal with these challenges in a coordinated manner. Therefore, the agriculture sector must maintain and increase food production and reduce emissions in the following years while ensuring economic and social sustainability (GI, 2022).

In this context, dairy and cattle farms are the country's main emitters of N_2O emissions, and their products' demand (dairy products and red meat) is expected to increase globally by 38% in 2050 (Komarek et al., 2021). The dairy and cattle farm's N_2O emissions are mainly a consequence of applying chemical N fertilisers as well as manure, urine and dung deposited directly or indirectly (land spreading) to soils to grow grass to feed cows and cattle animals (Lanigan et al., 2023). Therefore, the measures to reduce the sector's N_2O emissions focus on reducing N inputs into agriculture soils. The Teagasc GHG Marginal Abatement Cost Curve Analysis (MACC) report 2023 identifies the most cost-effective pathway to reduce greenhouse gas (GHG) emissions and enhance carbon sequestration in the Agricultural, Land-Use, Land-Use Change and Forestry sectors plus (Bio) energy (Lanigan et al., 2023). In the pathway identified, the reduction of N_2O emissions is crucial for achieving the target of reducing 25% of GHG by 2030. More specifically, the crucial mitigation measures are:

- Management of and reductions in the use of nitrogen fertilisers. Reduced N fertiliser application and altered fertiliser formulation (either protected urea or ammonium-based compound fertilisers).
- Technologies for achieving a reduction in nitrogen fertiliser use include the greater use of white and red clover, achieving optimum soil pH and soil P/K status in combination with enhanced use of legumes and multi-species swards and the use of Low Emissions Slurry Spreading (LESS).
- Altering fertiliser formulation, which is switching from CAN to protected urea or an ammonium-based compound.
- Reduced crude protein in animal feed concentrates will also contribute to reduced nitrogen loading in soils.

These mitigation measures are changes in management and adoption of technologies for reducing the application of chemical N fertilisers to soils. Two easy measures to implement in this context are (i) Low Emissions Slurry Spreading (LESS) and (ii) substitution towards protected urea fertiliser formulation, which increases nitrogen recovery in soils and farmers need less chemical N fertilisers for growing grass.

LESS is one of the most common measures that helps reduce N fertilisers. The cattle slurry was applied with vacuum tankers fitted with LESS technology instead of conventional broadcasting equipment; the slurry is delivered onto the soil in narrow bands, which reduced the surface area exposed to air compared to the broadcasting (Vangeli et al., 2022; Zilio et al., 2021). This resulted in better N recovery from organic fertiliser, which was assumed to replace fertiliser N. Vangeli et al. (2022) revised 100 experiments conducted in Ireland and the UK to study the application of different manure and excreta N sources such as dung, urine, and slurry, and their results show that LESS has a lower emission than dung and urine after 120 days of the application. The reduction found in N_2O emissions for LESS was 40% lower than dung and urine, mainly in coarse soils. Also, the difference varies among seasons, resulting from environmental factors such as rainfall, temperature, and soil moisture. Another research study on using LESS was conducted by Hafner et al. (2016), who used a semi-empirical model to quantify N_2O emissions for applying slurry. The analysis examines two levels of slurry application: low and high. According to the results, the low slurry application reduces emissions by 27%, while the high slurry application can reduce emissions by 37%.

On the other hand, the use of urea protected and urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) instead of calcium ammonium nitrate (CAN) is another relevant mitigation measure to reduce N_2O emissions. Harty et al. (2016) researched the impact of switching fertiliser formulation from calcium ammonium nitrate (CAN) to urea-based products as a potential mitigation strategy to reduce N_2O emissions. The results of this research show that the application of urea and urea + NBPT reduce N_2O emissions from 58% to 87%. Similar results were found by Rodriguez et al. (2021), but this research also studies the effect of applying urea + NBPT before the deposition of animal urine. The results show that the emissions from the application of urea + NBPT are higher post-application of the deposit of animal urine. Another research by Rahman et al. (2021) also studied the non-linear emission for different amounts of fertiliser applied. The results show that urea and urea + NBPT are less sensitive to increased urea and CAN fertilisers. Furthermore, Zilio et al. (2021) did research to compare LESS with conventional N fertiliser urea, and the results show that the low slurry application reduces emissions by 7%, and the urea application reduces emissions by 13%.

Even though LESS and urea protected are efficient for reducing N_2O emissions, their adoption and applicability depend on many factors(O'Brien et al., 2014), such as farm location, environmental conditions, type of production system, and market/policy conditions. Nevertheless, little evidence shows the economic impact on farms for adopting these measures. Previous research shows that reducing the use of chemical fertilisers, such as CAN, reduces the production of grasses for animal consumption, so production levels are affected. To counteract this effect, farmers resort to purchasing concentrates to complement or substitute animal feed. This paper aims to estimate the price and cross-price elasticities of demand for concentrate and home-produced feed and show whether it is affected by adopting (i) LESS and (ii) urea protected measures. Furthermore, the analysis includes grouping farms into four categories according to their biophysical conditions, which are related to their production levels and N_2O emissions(Francisco-Cruz et al., 2024).

The translog demand model (Christensen et al., 1973) is used for estimating price and cross-price elasticities . It is derived as a second-order Taylor series expansion about a point of the logarithm of an unknown twice differentiable function. The flexibility of the translog function and other similar flexible functional forms provide parameter estimates, values, and rate of change of an unknown function (Xu et al., 2009). The research work similar to the proposal in this paper was carried out by Tsakiridis et al. (Tsakiridis et al., 2024), who estimated a translog model for cattle farms in Ireland, differentiating by soil type using a panel database from 2000 to 2011. The results show that price and cross-price elasticities are inelastic and that the reaction to input prices is greater on farms with lower-quality soils.

2. Methodology

This section explains (i) the model proposed to estimate the price and cross-price elasticities of demand after adopting LESS and urea mitigation measures on feed substitution, (ii) the variables used to estimate the model, (iii) the data set used and (iV) definition of the farm groups according to their environmental characteristics.

2.1 Translog demand model

The model to estimate the price and cross-price elasticities of demand for concentrate and home-produced feed is based on the translog demand mode(Christensen et al., 1973). The model assumes a cost production (CP) as a function of factors: livestock animals used (LU), purchased concentrate (CO), home-produced feed (grass and crop production) (HP), veterinary and breeding services (V), and crop production (CR).

$$CP_{it} = \beta_0 + \beta_1 Q_{it} + \frac{1}{2}\beta_2 Q_{it}^2 + \beta_3 T_{it} + \frac{1}{2}\beta_4 T_{it}^2 + \beta_5 L_{it} + \frac{1}{2}\beta_6 L_{it}^2 + \sum_1^n \beta_7 P_{it} + \frac{1}{2}\sum_1^n \beta_8 P_n * P_{m_{it}} + \sum_1^n \beta_9 P_n * Q_{it} + \sum_1^n \beta_{10} P_n * L_{it} + \sum_1^n \beta_{11} P_n * T_{it} + \beta_{12} L * Q_{it} + \beta_{13} T * Q_{it} + \beta_{14} L * T_{it} \qquad \text{Eq. (1)}$$

Where Q represents farm production, T represents time, L is lad devoted to grass, and P is the price for n costs (LU, CO, HP, V, CR) for *i* farms in time *t*. The P variables are included in the model as the Laspeyers index for each input. According to Ray (Ray, 1982) the model needs simultaneous estimation with the derived input demand (S_i) and output share equation (S_Q), which are obtained by differentiating Eq. (1) with respect to input prices and the output share equation differentiating with respect to production as follows:

$$S_i = \frac{P_i X_i}{VC} = \frac{\delta CP}{\delta P_i} = \beta_i + \sum_i^n \beta_{ij} P_j + \beta_{iQ} Q + \beta_{iL} L + \beta_{iT} T \qquad \text{Eq. (2)}$$

$$S_Q = \frac{P_Q Q}{VC} = \frac{\delta CP}{\delta Q} = \beta_Q + \sum_i^n \beta_{iQ} P_j + \beta_{QQ} Q + \beta_{LQ} L + \beta_{TQ} T \qquad \text{Eq. (3)}$$

The model is estimated as the three-stage least squares (3SLS) using Eq. (1), (2) and (3), where the cost function is sufficiently homogeneous of degree one in prices P_i and the following conditions are satisfied:

$$\sum_{i=1}^4 \beta_i = 1 \qquad \text{Eq. (4)}$$

$$\sum_{i=1}^4 \beta_{ij} = \sum_{i=1}^4 \beta_{iQ} = \sum_{i=1}^4 \beta_{iL} = \sum_{i=1}^4 \beta_{iT} = 1 \qquad \text{Eq. (5)}$$

The price (β_7) and cross-price (β_8) elasticities of demand for each cost are obtained as the proportionate change in the demanded quantity of a cost n with respect to a proportionate change in its own price (η_{ii}) and change in the price of another cost (η_{ij}), respectively as follows:

$$\eta_{ii} = \frac{\delta X_i}{\delta P_i} = \frac{\beta_{ii+S_i^2-S_i}}{S_i} \quad , \quad i\text{= LU, CO, HP, V, CR} \qquad \text{Eq. (6)}$$

$$\eta_{ij} = \frac{\delta X_i}{\delta P_j} = \frac{\beta_{ij+s_i s_j}}{s_j} \quad , \; i, j = \text{LU, CO, HP, V, CR} \;\; (i \neq j) \qquad \text{Eq. (7)}$$

2.2 Variables

This section describes the variables used in the model in more detail. The estimation is conducted by dairy and cattle farms separately, because each type of farm has different characteristics linked with the production and management of farms.

The variable production for dairy farms represents milk production and livestock production, and for cattle farms, it is only cattle production, which sells calves, weanlings, stores, finished cattle, breeding and other cattle, plus the value of positive cattle inventory changes. The cost production (CP) is calculated by summing the total expenditure on used livestock animals (LU), purchased concentrate (CO), home-produced feed (grass) (HP), crop production (CR), and veterinary and breeding services (V).

The variable of livestock animals (LU) is the cost category of livestock animals' current year's expenditures on purchased livestock. Purchased concentrate (CO) represents the current expenditures for buying concentrate feed for livestock units. Home-produced feed (HP) summarises the cost of producing grass, including fertilisers, labour costs and machinery. Crop production (CR) is the cost of producing crops for feed livestock units; the crops considered are hay, fodder crops (maize silage, fodder beet, kale, fodder rape), and non-fodder crops (wheat, barley, oats, protein beans) on the farm. Veterinary and breeding services (V) is the total cost for veterinary and breeding services for livestock units. Finally, Land (L) is the area devoted to grass and crop production.

The price variables are obtained following the next steps. The prices for livestock units are a Laspeyres index for purchased animals. The price for home-produced feed and crop production are obtained by dividing direct production cost by yield (in tonnes). The price of concentrate feed is obtained by dividing expenditure on concentrate feed by purchased quantities. The price of veterinary and breeding services is the annual prices series data for an index of veterinary and breeding services prices obtained by the Irish Central Statistics Offices (CSO).

2.3 Groups of farms

Previous research shows that dairy and cattle production is influenced by a farm's environmental conditions (Di Falco & Zoupanidou, 2017; Tsakiridis et al., 2024). Also, the release of N_2O emissions is affected by soil characteristics and climate (Francisco-Cruz et al., 2024). In order to show if the biophysical conditions influence farmers' decision-making processes, it is used a farm classification based on the environmental characteristics of the farms defined by Francisco-Cruz et al. (2024). Table *1* shows the four categories used to extend the analysis presented in this paper. The four categories considered soil type, texture, moisture, and climate conditions. The first group has farms with good quality soils, low soil moisture, and good climate conditions to produce grass and crops. The second and third groups of farms have regular quality soils; the soil texture for the categories are mainly sandy loam and loam, and the levels of rain are higher than category one. Finally, the last group represents farms with lower-quality soils; they are organic-mineral, the soil texture is clay loam, and the soil drainage is poor.

Table 1. Environmental category of the farms.

Group of farms	Group description
1	Soil type: Organic-mineral (62%); Soil texture: Sandy loam (42%); Soil drainage: Well (63%); Soil Moisture: 24; Rainfall: 920 mm; and Temperature: 10.02 ºC
2	Soil type: Organic-mineral (59%); Soil texture: Sandy loam (43%); Soil drainage: Well (55%); Soil Moisture: 25%; Rainfall: 965 mm; and Temperature: 9.90 ºC
3	Soil type: Organic-mineral (56%); Soil texture: Loam (36%); Soil drainage: Well (39%); Soil Moisture: 25%; Rainfall: 1,004 mm; and Temperature: 9.90 ºC
4	Soil type: Mineral (37%); Soil texture: Clay loam (33%); Soil drainage: Poorly (53%); Soil Moisture: 26%; Rainfall: 1,090 mm; and Temperature: 9.84 ºC

Note: The table shows the farm's category defined by Francisco-Cruz et al. (2024) according to soil characteristics and climate conditions.

2.4 Data framework

To estimate the translog function presented in Eq. 1, we used the Teagasc National Farm Survey (NFS) from 2014 to 2021, which is an unbalanced data panel of farms with detailed information on agricultural activity. Due to the characteristics of each type of farm, we estimated a cost function for dairy farms and another for cattle farms to be more precise with the interpretation of the results. Table *2* shows the main characteristics of the farms included in the NFS. On average, the survey includes a sample of 900 farms per year and weighting the NFS represents around 90 thousand Irish farms. Farms surveyed have, on average, a farm size of 45 hectares with a stocking rate of unit animals around 1.43. However, a lot of variability among farms is shown in the standard deviation and the range between the minimum and maximum values.

Additionally, using chemical fertilisers such as CAN is 77 N kg per hectare on average, and the analysed period has been maintained. For its part, the use of protected urea is 40 N kg per hectare and has a moderate positive trend in the analysed period. The application of Slurry has increased, and the application of solid manure has decreased slightly.

Table 2. Farm's characteristics, 2014-2021.

Year	Stats	2014	2015	2016	2017	2018	2019	2020	2021
No. Farms in the NFS	No.	929	993	895	896	904	884	840	837
Farms represented	No.	88,652	91,126	92,822	90,907	89,115	86,838	85,568	84,929
Average area size (ha.)	Mean	44.1	46.6	43.0	43.6	44.2	45.0	44.7	44.9
	SD	42.0	45.1	48.8	44.7	45.0	46.2	37.9	36.0
	Min	7.3	3.7	7.3	7.3	8.0	8.0	7.4	7.4
	Max	1116.6	1116.6	1116.6	1116.6	1116.6	1116.6	1116.6	1116.6
Stoking rate (UA)	Mean	1.37	1.36	1.42	1.45	1.43	1.41	1.39	1.43
	SD	0.59	0.63	0.61	0.66	0.62	0.63	0.62	0.64
	Min	0.02	0.02	0.03	0.01	0.04	0.04	0.01	0.02
	Max	3.95	7.46	4.14	4.53	4.51	4.96	4.69	4.66
CAN per ha (N kg.)	Mean	77.2	73.6	72.6	76.1	83.6	72.5	73.4	76.5
	SD	60.6	56.8	54.7	59.9	61.5	53.3	52.7	53.8
	Min	0.4	0.7	0.8	1.1	0.3	0.6	0.7	1.0
	Max	732.6	396.4	342.5	506.6	374.5	299.4	499.1	504.2
Urea per ha (N kg.)	Mean	36.8	36.1	41.5	41.7	43.4	45.3	44.3	41.1
	SD	31.9	32.4	36.5	36.7	36.4	41.1	47.0	39.1
	Min	0.7	1.7	0.9	1.2	1.1	0.7	0.7	1.2
	Max	231.2	202.5	226.8	175.0	197.7	284.2	349.2	296.1
Slurry application per ha (N kg.)	Mean	31.9	36.5	36.4	42.4	43.9	41.5	40.7	40.1
	SD	19.0	21.6	21.9	25.8	26.3	26.2	25.1	23.7
	Min	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
	Max	121.3	174.2	119.6	141.0	161.4	171.1	127.1	127.3
Solid manure application per ha (N kg.)	Mean	10.9	10.6	11.2	11.0	10.4	9.6	9.6	9.2
	SD	9.1	11.1	12.6	12.6	11.4	10.8	11.1	9.4
	Min	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max	71.8	108.5	118.8	93.6	87.7	70.8	80.5	84.9

Note: The table shows the main farm's characteristics reported in the NFS from 2014 to 2021.

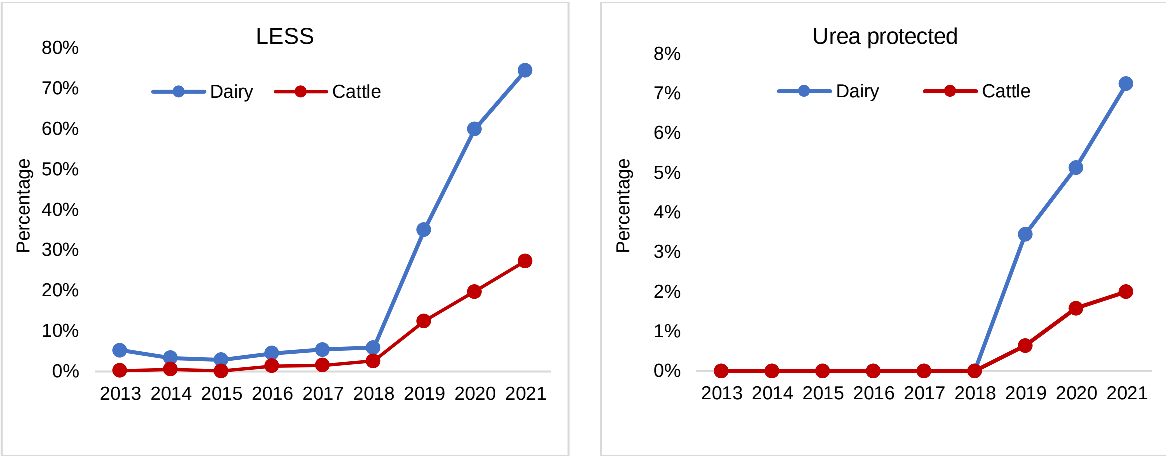
3. Results

This section presents the results obtained after applying the translog model. It shows the adoption of the mitigation measures analysed, which are LESS and urea protected, and the changes at the farm level in N_2O emissions, grass production and purchase concentrates. Then, the own and cross-price elasticities are presented, differentiated by farms with and without mitigation measures. Finally, the analysis considering farms' environmental conditions is presented.

3.1 LESS and urea protected adoption.

Figure *1* presents the percentage of Dairy and Cattle farms reported in the NFS that have adopted mitigation measures to reduce N_2O emissions in Ireland from 2014 to 2021. In the case of the LESS measure, there was a low percentage of adoption between 2014 and 2018; less than 10% of farms used this measure. However, since 2019, the percentage of farms that use this measure has increased considerably, mainly in Dairy farms, which by 2021 reached 70% of LESS application, and for Cattle farms, exceeded 30%. Conversely, in the case of urea protection, there was low adoption in the period analysed. Although it increased considerably after 2018, the percentage is lower than 10% for Dairy farms and lower than 3% for Cattle farms.

Figure 1. Mitigation measures adoption.



Note: The figure reports the percentage of Dairy and Cattle farms that have adopted the mitigation measures LESS and urea protected to reduce N_2O emissions reported in the NFS.

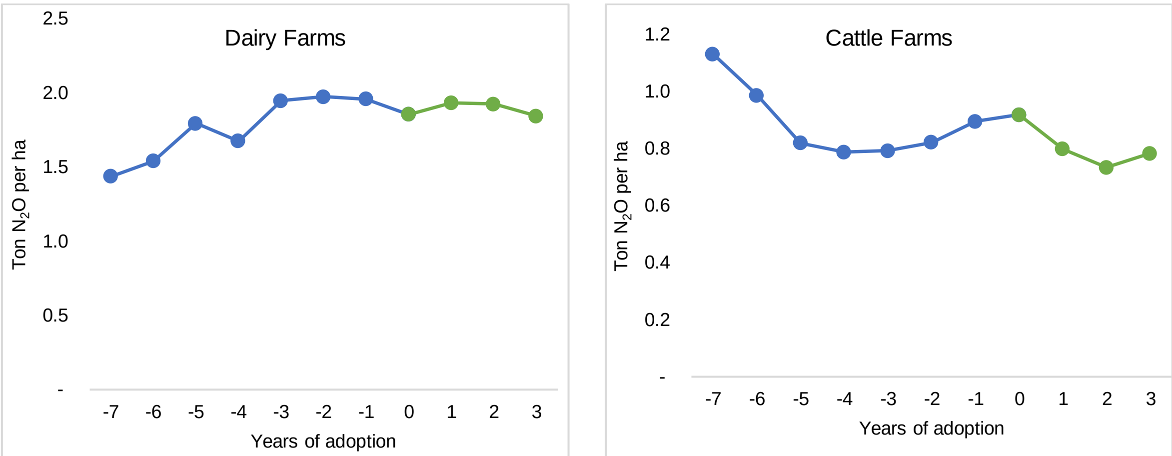
In this paper, we define a treatment group of farms that have adopted mitigation measures, those that use LESS or protected urea separately or both measures, and we identify as a comparison group the farms that have not adopted any of these measures.

To analyse changes in farms after using mitigation measures, we identified the year in which farms began using them and analysed trends before and after adoption in N_2O emissions, grass production costs, and the purchase of concentrates. Figure *2* shows the graphs corresponding to this analysis. On the X axis, the years before or after the adoption are presented, marked by year zero. In the case of N_2O emissions, it is observed that for Dairy farms, there was a positive trend before the adoption of mitigation measures and that it became a constant trend after the adoption. In the case of Cattle farms, a positive trend is observed in the 4 years before the adoption and a decrease in emissions after adopting mitigation measures.

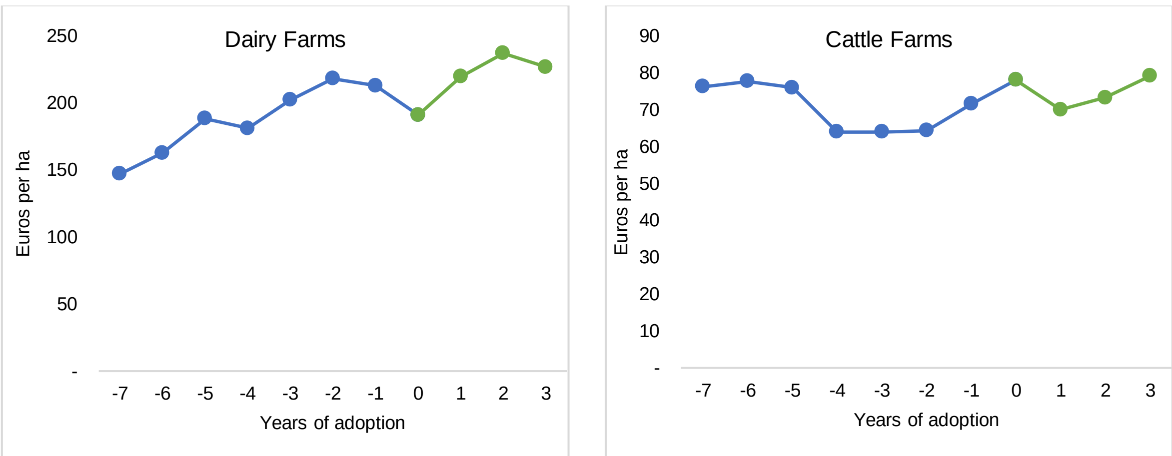
In the case of the costs associated with grass production, a positive trend is observed before adoption and remains positive after adoption in the case of Dairy farms. In the case of Cattle farms, a positive trend is observed after adoption. However, it is important to mention that the costs of producing grass are lower on Cattle farms than on Dairy farms. Regarding the purchase of concentrates, it is observed that Dairy farms have a positive trend before and after the adoption. In the case of Cattle farms, a constant trend is observed in the purchase of concentrates before and after the adoption of the measures.

Figure 2. Changes after adopting mitigation measures.

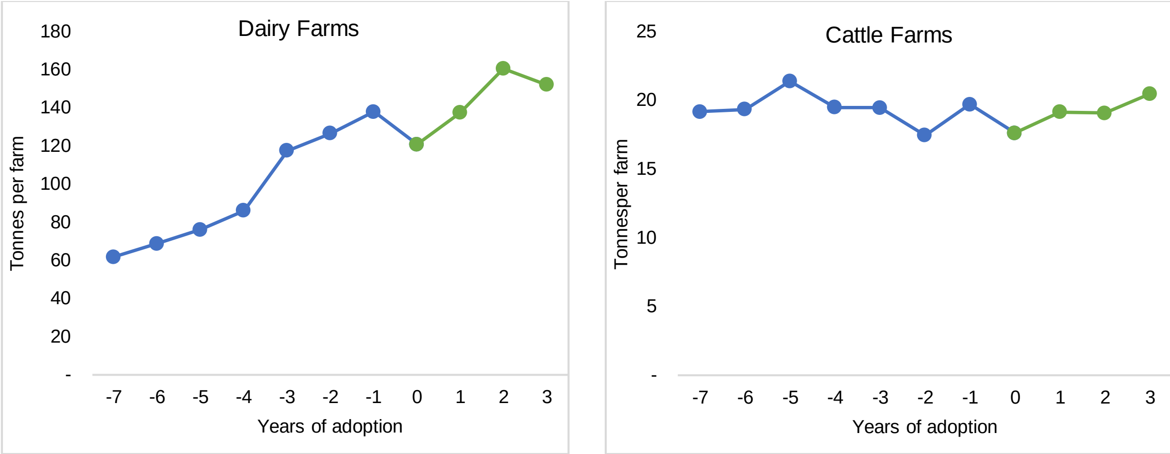
N_2O Emissions



Grass land cost per Ha



Purchased concentrates

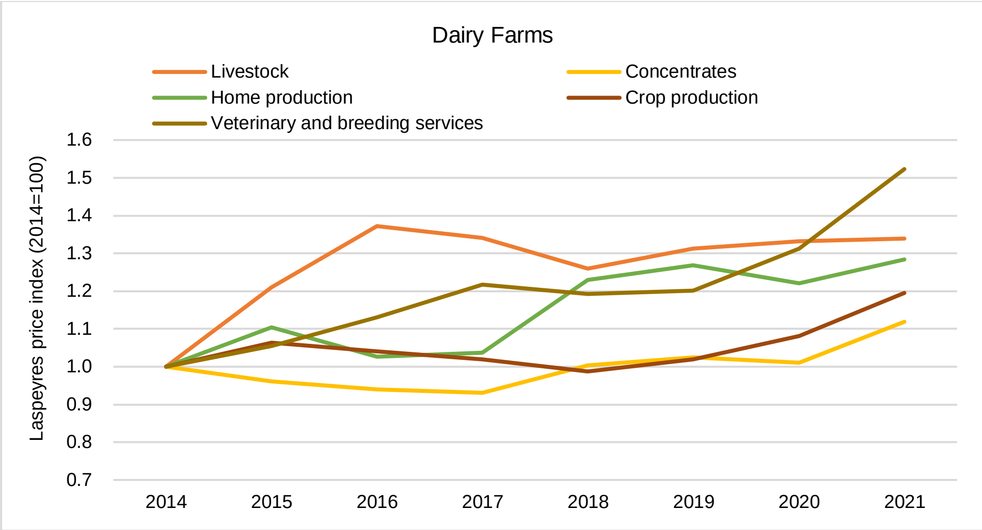


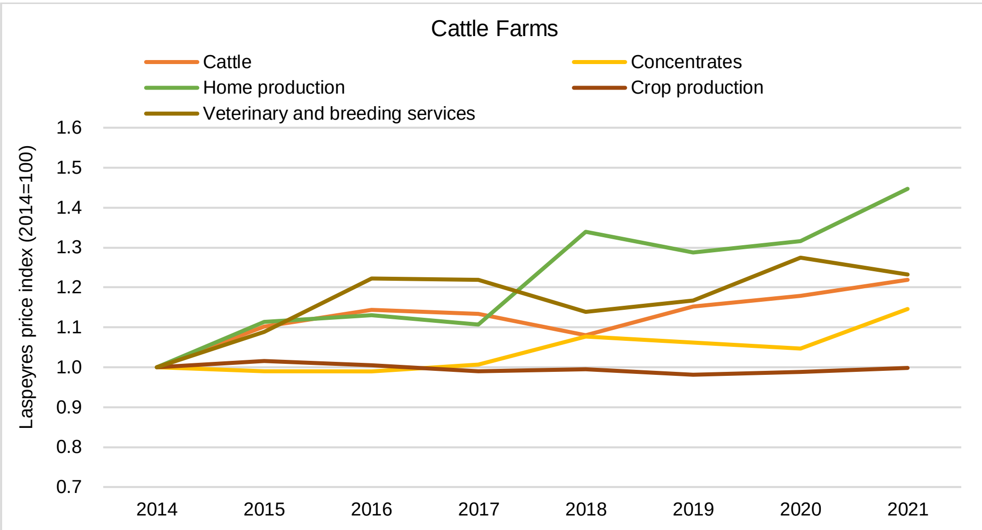
Note: The figure shows the trends before and after adopting mitigation measures. Year 0 represents the year in which any of the mitigation measures analysed were adopted.

3.2 Input price trend

Input prices are important in the analysis of this paper. As it was mentioned before, the input prices are obtained as the Laspeyres index for each input included in Equation 1. Figure 3 shows the price trend identified by type of farm. In Dairy farms, livestock units, home production and veterinary services have increased their prices considerably. Livestock prices have increased by around 30% since 2016 compared with 2014, and home production has increased by around 20%. On the other hand, Cattle farms show an important increase in prices in home production, veterinary and breeding services, and cattle units. The price of concentrates has increased by less than 10% in the period analysed in both types of farms.

Figure 3. Input price trend by type of farm.





Note: The figure shows the input price trends by dairy and cattle farms from 2014 to 2021. The prices are presented as the Laspeyres index with base year 2014=100.

3.2 Own price elasticities

The translog function was estimated for Dairy and Cattle farms separately. For both groups, three estimations were obtained. The first estimation was for all farms to get baseline results; the second estimation was for the treatment group of farms that have adopted the mitigation measures; the third estimation was for the group of farms without mitigation measures. The estimations using Equation 1 are reported in Annex A, and the price elasticities using Equation 6 are reported in this section.

Table 3 shows the results of the price elasticities for livestock inputs, concentrates and home production, both for Dairy and Cattle farms. The results show negative elasticities for the three inputs, and the values lower than 1 indicate that they are inelastic. The elasticities for livestock are greater than that of concentrates, and that of concentrates is greater than those of home production. The elasticities for Cattle farms are greater than the elasticities for Dairy farms, which means that Cattle farms have a greater reaction to the price changes of the inputs analysed. For example, if the price of concentrates increases by 1%, Cattle farms reduce their demand for concentrates by 0.46%, while Dairy farms reduce their demand by 0.30%.

Table 3. Price elasticities by Dairy and Cattle farms.

Input	Dairy	Cattle
Livestock	-0.62	-0.79
Concentrates	-0.30	-0.46
Home production	-0.19	-0.36

Note: The table reports the price elasticities for inputs livestock, concentrates and home production by type of farm.

The elasticities obtained by differentiating the group with and without adoptions of mitigation measures are presented in Table 4. The results show greater elasticities for the Cattle farms than the Dairy farms, and the elasticities for the group with adoption are greater than the elasticities of the untreated group. However, the differences are less than 0.06% in the case of concentrates and 0.10% for home production.

Table 4. Price elasticities by Dairy and Cattle farms distinguish with and without the adoption of mitigation measures.

	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock	-0.64	-0.60	-0.82	-0.77
Concentrates	-0.34	-0.28	-0.47	-0.38
Home production	-0.27	-0.17	-0.35	-0.34

Note: The table reports the price elasticities for livestock, concentrates and home production inputs by type of farm and with adoption or not adoption of mitigation measures.

3.3 Cross price elasticities

The cross-price elasticities make identifying the degree of substitution between inputs possible. Cross-elasticities were obtained using equation 7, and the results are shown in Table *5*. The cross-price elasticity between livestock and concentrates has a positive and low value, indicating that they are complements. In the case of cross-elasticity between animals and costs for producing grass, the elasticity is positive, which means they complement, too; if there is an increase in animal price, the demand required for grass production would be lower. Finally, concentrate substitution and grass production have a negative elasticity, which means they are substitutes; a reduction in the price of concentrates can reduce the demand for grass home production. The cross-price elasticity between concentrates and home production is higher in the case of Dairy farms.

Table 5. Cross price elasticities by Dairy and Cattle farms.

Input	Dairy	Cattle
Livestock/Concentrates	0.124	0.206
Livestock/Home prod	0.373	0.125
Concentrates/ Home prod	-0.209	-0.122

Note: The table reports the cross-price elasticities for inputs livestock, concentrates and home production by type of farm.

The cross-price elasticities obtained by differentiating between adopted and no adopted groups are presented in Table 6. In this case, it is observed that the adopted group has cross-elasticities with higher values than the no adopted group, mainly in Dairy farms. In the case of cross-elasticity between concentrates and grass production, the treated group has a higher elasticity, which represents a greater reaction to price changes.

Table 6. Cross-price elasticities by Dairy and Cattle farms distinguish with and without the adoption of mitigation measures.

	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock/Concentrates	0.131	0.104	0.214	0.203
Livestock/Home prod	0.393	0.362	0.145	0.101
Concentrates/ Home prod	-0.219	-0.189	-0.153	-0.104

Note: The table reports the cross-price elasticities for livestock, concentrates, and home production inputs by type of farms and t with adoption or not adoption of mitigation measures.

3.4 Environmental influence

Additionally, Table *7* reports the cross-price elasticity by group of farms according to their environmental conditions. Farms in better environmental conditions tend to use fewer inputs for local production, so they are less affected by adopting mitigation measures to reduce N_2O emissions (Group 1). This contrasts with farms that use a greater amount of inputs for grass production, which shows a greater reaction to changes in the prices of concentrates and local production (Group 4).

Table 7. Cross-price elasticities by type farms, with and without the adoption of mitigation measures and environmental conditions.

	Group 1			
	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock/Concentrates	0.101	0.091	0.122	0.115
Livestock/Home prod	0.254	0.135	0.101	0.090
Concentrates/ Home prod	-0.123	-0.115	-0.112	-0.087
	Group 2			
	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock/Concentrates	0.112	0.102	0.135	0.203
Livestock/Home prod	0.267	0.231	0.121	0.099
Concentrates/ Home prod	-0.143	-0.136	-0.129	-0.097
	Group 3			
	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock/Concentrates	0.125	0.105	0.155	0.203
Livestock/Home prod	0.287	0.305	0.138	0.110
Concentrates/ Home prod	-0.165	-0.176	-0.148	-0.109
	Group 4			
	Dairy		Cattle	
Input	Adopted	No Adopted	Adopted	No Adopted
Livestock/Concentrates	0.142	0.110	0.214	0.203
Livestock/Home prod	0.412	0.387	0.159	0.116
Concentrates/ Home prod	-0.210	-0.196	-0.174	-0.110

Note: The table reports the cross-price elasticities for inputs livestock, concentrates and home production by type of farm, with adoption or not adoption of mitigation measures, and environmental conditions.

4. Conclusions and discussion

This paper contributes to the economic analysis of adopting mitigation measures to reduce N_2O emissions in the agricultural sector. Our findings underscore the feasibility of these mitigation measures for farmers seeking to sustain home production feed while concurrently diminishing N_2O emissions. The estimated elasticities for the analysed inputs are inelastic for Dairy and Cattle farms. The results for Cattle farms are similar to those reported by Tsakiridis et al. (2024).

With regard to farms that have adopted mitigation measures, we find that they have greater elasticities than farms that have not yet adopted measures. However, it is important to consider that the percentage of farms with mitigation measures is low, particularly in the adoption of urea protected. Nevertheless, it is important to mention that the economic effect is small compared to the emission reductions due to the adoption of the mitigation measures analysed.

An integral aspect emerges concerning the necessity for concurrent economic policies or subsidies to facilitate and incentivize the comprehensive adoption of these mitigation measures. This underscores the importance of an integral approach, where economic instruments complement the environmental objectives, ensuring a more effective and sustainable transition toward reduced N_2O emissions in agriculture.

5. Reference

Christensen, L. R., Jorgenson, D. W., & Lau, L. J. (1973). Transcendental Logarithmic Production Frontiers. *The Review of Economics and Statistics*, *55*(1), 28–45.

Di Falco, S., & Zoupanidou, E. (2017). Soil fertility, crop biodiversity, and farmers' revenues: Evidence from Italy. *Ambio*, *46*(2), 162–172. https://doi.org/10.1007/s13280-016-0812-7

Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, A., Kent, B., MacFarlane, B., Monaghan, S., Murphy, J., Ponzi, J., & Ryan, A. M. (2023). *NIR 2023* (p. 450). Environmental Protection Agency. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/NIR-2023-Final_v3.pdf

Francisco-Cruz, C. A., Buckley, C., Breen, J., & Lanigan, G. (2024). Estimating Nitrous Oxide (N2O) emissions from managed soils at higher spatial resolution in the Republic of Ireland. *Ecological Indicators*, *158*, 111471. https://doi.org/10.1016/j.ecolind.2023.111471

GI. (2022). *Climate Action Plan 2023*. Government of The Republic of Ireland.

Harty, M. A., Forrestal, P. J., Watson, C. J., McGeough, K. L., Carolan, R., Elliot, C., Krol, D., Laughlin, R. J., Richards, K. G., & Lanigan, G. J. (2016). Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations. *Science of The Total Environment*, *563–564*, 576–586. https://doi.org/10.1016/j.scitotenv.2016.04.120

Komarek, A. M., Dunston, S., Enahoro, D., Godfray, H. C. J., Herrero, M., Mason-D'Croz, D., Rich, K. M., Scarborough, P., Springmann, M., Sulser, T. B., Wiebe, K., & Willenbockel, D. (2021). Income, consumer preferences, and the future of livestock-derived food demand. *Global Environmental Change*, *70*, 102343. https://doi.org/10.1016/j.gloenvcha.2021.102343

Lanigan, G. J., Hanrahan, K., & Richards, K. G. (2023). *An Updated Analysis of the Greenhouse Gas Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030*. Teagasc.

O'Brien, D., Shalloo, L., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Hanrahan, K., Lalor, S., Lanigan, G., Thorne, F., & Schulte, R. (2014). An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. *Environmental Science & Policy*, *39*, 107–118. https://doi.org/10.1016/j.envsci.2013.09.001

Rahman, N., Richards, K. G., Harty, M. A., Watson, C. J., Carolan, R., Krol, D., Lanigan, G. J., & Forrestal, P. J. (2021). Differing effects of increasing calcium ammonium nitrate, urea and urea + NBPT fertiliser rates on nitrous oxide emission factors at six temperate grassland sites in Ireland. *Agriculture, Ecosystems & Environment*, *313*, 107382. https://doi.org/10.1016/j.agee.2021.107382

Ray, S. C. (1982). A Translog Cost Function Analysis of U.S. Agriculture, 1939–77. *American Journal of Agricultural Economics*, *64*(3), 490–498. https://doi.org/10.2307/1240641

Rodriguez, M. J., Saggar, S., Berben, P., Palmada, T., Lopez-Villalobos, N., & Pal, P. (2021). Use of a urease inhibitor to mitigate ammonia emissions from urine patches. *Environmental Technology*, *42*(1), 20–31. https://doi.org/10.1080/09593330.2019.1620345

Tsakiridis, A., Hanrahan, K., Breen, J., O’Donoghue, C., & Wallace, M. (2024). Modelling pasture-based beef production costs using panel data from farms with different soil quality. *Review of Agricultural, Food and Environmental Studies*. https://doi.org/10.1007/s41130-023-00203-8

Vangeli, S., Cardenas, L. M., Posse, G., Chadwick, D. R., Krol, D. J., Thorman, R. E., Lanigan, G. J., & Misselbrook, T. H. (2022). Revisiting sampling duration to estimate N2O emission factors for manure application and cattle excreta deposition for the UK and Ireland. *Journal of Environmental Management*, *322*, 116037. https://doi.org/10.1016/j.jenvman.2022.116037

Xu, Z., Guan, Z., Jayne, T. S., & Black, R. (2009). Factors influencing the profitability of fertilizer use on maize in Zambia. *Agricultural Economics*, *40*(4), 437–446. https://doi.org/10.1111/j.1574-0862.2009.00384.x

Zilio, M., Pigoli, A., Rizzi, B., Geromel, G., Meers, E., Schoumans, O., Giordano, A., & Adani, F. (2021). Measuring ammonia and odours emissions during full field digestate use in agriculture. *Science of The Total Environment*, *782*, 146882. https://doi.org/10.1016/j.scitotenv.2021.146882

Annex A.

Table 8. Translog function by Dairy and Cattle farms.

Variable	Dairy	Cattle
Production (Q)	-0.129	-0.498***
	(0.091)	(0.131)
Production2 (Q2)	0.039***	0.085***
	(0.001)	(0.006)
Time (T)	0.035	-0.013
	(0.067)	(0.051)
Time2 (T2)	0.009***	0.004*
	(0.001)	(0.002)
Price		
Livestock	0.935*	0.476
	(0.404)	(0.376)
Concentrates	0.549	0.169
	(0.392)	(0.217)
Home production	0.238	0.758***
	(0.350)	(0.167)
Crops production	0.176	0.300
	(0.399)	(0.394)
Veterinary and breading	0.053	0.249*
	(0.199)	(0.112)
Cross price		
Livestock/Concentrates	0.358	0.014
	(0.226)	(0.065)
Livestock/Home prod	0.027	0.034
	(0.179)	(0.050)
Livestock/Crops prod	0.270	0.183
	(0.200)	(0.151)
Livestock/Vet and Bred	0.110	0.060
	(0.101)	(0.034)
Concentrates/ Home prod	0.030	0.031
	(0.024)	(0.017)
Concentrates/Crops prod	0.001	-0.094
	(0.018)	(0.075)
Concentrates/Vet and Bred	0.012	-0.013
	(0.015)	(0.018)
Home prod/Crops prod	-0.034	0.009
	(0.019)	(0.083)
Home prod/Vet and Bred	-0.012	-0.018
	(0.014)	(0.013)
Crops prod/Vet and Bred	-0.030	-0.094
	(0.020)	(0.052)
Control variables		
Land (L)	-0.011	0.469*
	(0.237)	(0.186)
Land2 (L2)	0.015	-0.092***

Variable	Dairy	Cattle
	(0.008)	(0.017)
Production (Q)/Livestock	-0.171**	0.005
	(0.061)	(0.045)
Production (Q)/Concentrates	-0.004	-0.024
	(0.022)	(0.021)
Production (Q)/Home prod	-0.007	-0.094***
	(0.018)	(0.016)
Production (Q)/Crops prod	0.044	-0.002
	(0.027)	(0.047)
Production (Q)/Vet and Bred	-0.026	-0.020
	(0.013)	(0.011)
Land (L)/Livestock	0.244	0.078
	(0.162)	(0.063)
Land (L)/Concentrates	0.035	0.025
	(0.031)	(0.034)
Land (L)/Home prod	-0.013	0.077**
	(0.024)	(0.024)
Land (L)/Crops prod	-0.038	-0.118
	(0.040)	(0.094)
Land (L)/Vet and Bred	0.045*	0.019
	(0.019)	(0.019)
Time (T)/Livestock	0.002	0.031
	(0.040)	(0.020)
Time (T)/Concentrates	-0.029***	0.002
	(0.006)	(0.008)
Time (T)/Home prod	0.019**	-0.003
	(0.006)	(0.006)
Time (T)/Crops prod	-0.003	-0.014
	(0.005)	(0.023)
Time (T)/Vet and Bred	0.001	-0.006
	(0.003)	(0.005)
Time (T)/ Production (Q)	-0.010**	-0.011*
	(0.004)	(0.005)
Time (T)/Land (L)	0.002	0.014
	(0.005)	(0.007)
Constant	6.078***	5.924***
	(0.632)	(0.652)

Table 9. Translog function by Dairy farms and group of farms.

	Group of farms			
Variable	1	2	3	4
Production (Q)	0.469	-0.412	1.432***	-0.054
	(0.403)	(0.368)	(0.425)	(0.280)
Production2 (Q2)	0.022	0.047***	-0.007	0.040***
	(0.014)	(0.002)	(0.014)	(0.009)
Time (T)	-0.253	-0.549*	-0.025	-0.111

	Group of farms			
Variable	1	2	3	4
	(0.138)	(0.235)	(0.263)	(0.151)
Time2 (T2)	0.009***	0.006**	0.011***	0.009***
	(0.002)	(0.002)	(0.002)	(0.002)
Price				
Livestock	0.857	0.823	0.790	0.981
	(1.569)	(1.623)	(1.558)	(1.292)
Concentrates	0.466	0.538	0.817	0.896
	(1.003)	(1.544)	(1.281)	(0.684)
Home production	0.762	0.555	0.500	0.928
	(0.975)	(1.320)	(0.889)	(0.679)
Crops production	0.957	0.754	0.902**	0.546
	(1.764)	(1.696)	(1.888)	(1.380)
Veterinary and breading	0.128	0.585	0.205	0.305
	(0.462)	(0.881)	(0.603)	(0.507)
Cross price				
Livestock/Concentrates	-0.506	-0.052	-0.287	-0.745
	(0.462)	(1.022)	(0.839)	(0.384)
Livestock/Home prod	0.191	0.303	0.008*	0.411
	(0.556)	(0.840)	(0.451)	(0.380)
Livestock/Crops prod	0.875	0.268	0.761	0.020
	(0.609)	(1.066)	(1.005)	(0.321)
Livestock/Vet and Bred	0.262	0.683	0.294	0.139
	(0.252)	(0.569)	(0.308)	(0.325)
Concentrates/ Home prod	0.116	0.026	0.033	0.072
	(0.064)	(0.074)	(0.053)	(0.042)
Concentrates/Crops prod	0.042	0.037	0.063	0.037
	(0.225)	(0.152)	(0.062)	(0.029)
Concentrates/Vet and Bred	0.007	0.077	-0.021	0.052
	(0.025)	(0.052)	(0.031)	(0.033)
Home prod/Crops prod	-0.210	-0.017	0.254	-0.012
	(0.174)	(0.142)	(0.177)	(0.033)
Home prod/Vet and Bred	-0.014	-0.035	-0.003	-0.014
	(0.029)	(0.044)	(0.034)	(0.027)
Crops prod/Vet and Bred	-0.044	0.032	-0.087	-0.008
	(0.122)	(0.092)	(0.126)	(0.035)
Control variables				
Land (L)	-0.111	-0.514	-0.891	-0.303
	(0.455)	(1.233)	(0.893)	(0.481)
Land2 (L2)	0.001	-0.007	0.087***	0.013
	(0.023)	(0.023)	(0.022)	(0.016)
Production (Q)/Livestock	-0.289	-0.119	-0.584*	-0.164
	(0.191)	(0.268)	(0.237)	(0.168)
Production (Q)/Concentrates	-0.086	-0.116*	-0.010	0.048
	(0.055)	(0.046)	(0.060)	(0.048)
Production (Q)/Home prod	0.008	0.050	-0.034	0.033
	(0.053)	(0.059)	(0.037)	(0.041)
Production (Q)/Crops prod	0.098	-0.067	0.232	-0.057

	Group of farms			
Variable	1	2	3	4
	(0.170)	(0.103)	(0.153)	(0.108)
Production (Q)/Vet and Bred	0.051	-0.060	-0.027	-0.037
	(0.031)	(0.035)	(0.040)	(0.025)
Land (L)/Livestock	0.461	0.595	0.575	0.370
	(0.294)	(0.898)	(0.628)	(0.335)
Land (L)/Concentrates	0.120	0.060	0.072	-0.089
	(0.064)	(0.070)	(0.082)	(0.065)
Land (L)/Home prod	-0.036	-0.128	0.022	-0.000
	(0.069)	(0.068)	(0.051)	(0.058)
Land (L)/Crops prod	-0.231	0.129	-0.134	0.072
	(0.262)	(0.150)	(0.228)	(0.100)
Land (L)/Vet and Bred	-0.030	0.058	0.055	0.007
	(0.043)	(0.043)	(0.047)	(0.036)
Time (T)/Livestock	0.093	0.265	0.046	0.089
	(0.070)	(0.159)	(0.180)	(0.098)
Time (T)/Concentrates	-0.035***	-0.019	-0.038**	-0.029**
	(0.010)	(0.016)	(0.014)	(0.011)
Time (T)/Home prod	-0.008	0.019	0.019	-0.000
	(0.012)	(0.015)	(0.012)	(0.011)
Time (T)/Crops prod	0.065	0.002	-0.006	-0.010
	(0.040)	(0.016)	(0.020)	(0.009)
Time (T)/Vet and Bred	0.008	-0.014	0.007	-0.003
	(0.005)	(0.009)	(0.008)	(0.007)
Time (T)/ Production (Q)	-0.004	0.011	-0.009	-0.010
	(0.009)	(0.009)	(0.010)	(0.007)
Time (T)/Land (L)	-0.002	-0.005	-0.007	0.008
	(0.010)	(0.012)	(0.011)	(0.009)
Constant	3.231	12.256***	-1.176	6.176***
	(2.548)	(2.078)	(2.667)	(1.833)

Table 10. Translog function by Cattle farms and group of farms.

	Group of farms			
Variable	1	2	3	4
Production (Q)	-8.525***	-0.056	-1.470***	-0.199
	(2.038)	(0.223)	(0.304)	(0.410)
Production2 (Q2)	0.125*	0.062***	0.135***	0.075***
	(0.054)	(0.011)	(0.012)	(0.011)
Time (T)	0.099	0.016	-0.106	0.109
	(1.173)	(0.086)	(0.113)	(0.182)
Time2 (T2)	0.007	0.002	0.004	0.004
	(0.006)	(0.003)	(0.003)	(0.003)
Price				
Livestock	0.564	0.766	0.871	0.798
	(10.582)	(0.700)	(0.841)	(1.493)
Concentrates	0.567*	0.135	0.420	0.574

	Group of farms			
Variable	1	2	3	4
	(1.732)	(0.328)	(0.665)	(0.892)
Home production	0.649	0.846*	0.638	0.224
	(2.017)	(0.331)	(0.413)	(0.817)
Crops production	0.603	0.555	0.165	0.217
	(7.770)	(0.700)	(0.902)	(1.197)
Veterinary and breading	0.880	0.230	0.547*	-0.217
	(2.753)	(0.198)	(0.238)	(0.357)
Cross price				
Livestock/Concentrates	0.115	0.004	0.079	0.051
	(0.424)	(0.110)	(0.131)	(0.187)
Livestock/Home prod	0.255	0.077	0.133	0.203
	(0.228)	(0.083)	(0.108)	(0.115)
Livestock/Crops prod	13.823	-0.035	-0.416	0.759
	(9.781)	(0.246)	(0.632)	(1.148)
Livestock/Vet and Bred	0.054	0.089	0.020	0.040
	(0.245)	(0.054)	(0.065)	(0.097)
Concentrates/ Home prod	0.216*	0.043	0.031	0.000
	(0.104)	(0.035)	(0.048)	(0.040)
Concentrates/Crops prod	4.002*	-0.098	0.089	-0.514
	(1.749)	(0.088)	(0.383)	(0.736)
Concentrates/Vet and Bred	-0.132	-0.000	0.006	-0.077
	(0.080)	(0.029)	(0.030)	(0.054)
Home prod/Crops prod	-0.086	-0.200	0.058	-0.037
	(1.625)	(0.153)	(0.265)	(0.755)
Home prod/Vet and Bred	-0.030	0.057*	-0.003	-0.080*
	(0.053)	(0.025)	(0.023)	(0.032)
Crops prod/Vet and Bred	-0.227	0.003	-0.081	0.015
	(2.673)	(0.091)	(0.140)	(0.282)
Control variables				
Land (L)	23.672*	0.520	0.169	0.665
	(9.224)	(0.326)	(0.533)	(0.917)
Land2 (L2)	0.040	-0.112***	-0.087**	-0.103**
	(0.093)	(0.034)	(0.030)	(0.038)
Production (Q)/Livestock	-0.154	0.022	-0.027	0.144
	(0.358)	(0.085)	(0.082)	(0.108)
Production (Q)/Concentrates	-0.108	-0.012	0.061	-0.035
	(0.150)	(0.035)	(0.049)	(0.043)
Production (Q)/Home prod	-0.368***	-0.121***	-0.137***	-0.020
	(0.107)	(0.032)	(0.030)	(0.036)
Production (Q)/Crops prod	7.073***	-0.020	0.058	-0.285
	(1.829)	(0.070)	(0.152)	(0.300)
Production (Q)/Vet and Bred	-0.078	-0.032	-0.067**	0.030
	(0.076)	(0.021)	(0.021)	(0.021)
Land (L)/Livestock	0.292	0.203	0.103	0.028
	(0.421)	(0.121)	(0.126)	(0.143)
Land (L)/Concentrates	0.086	0.038	-0.129	0.043
	(0.218)	(0.069)	(0.071)	(0.068)

	Group of farms			
Variable	1	2	3	4
Land (L)/Home prod	0.138	0.206***	0.152**	-0.042
	(0.173)	(0.052)	(0.046)	(0.049)
Land (L)/Crops prod	-24.219**	-0.077	0.005	-0.177
	(9.134)	(0.125)	(0.443)	(0.813)
Land (L)/Vet and Bred	0.035	0.027	0.076*	-0.046
	(0.096)	(0.038)	(0.036)	(0.040)
Time (T)/Livestock	0.083	0.024	0.062	-0.026
	(0.099)	(0.033)	(0.036)	(0.042)
Time (T)/Concentrates	0.023	-0.014	-0.004	0.007
	(0.043)	(0.014)	(0.015)	(0.021)
Time (T)/Home prod	0.003	0.001	0.001	-0.023
	(0.030)	(0.012)	(0.012)	(0.012)
Time (T)/Crops prod	-0.276	-0.014	-0.008	0.026
	(1.190)	(0.031)	(0.078)	(0.152)
Time (T)/Vet and Bred	-0.011	-0.009	0.001	0.017
	(0.024)	(0.009)	(0.007)	(0.011)
Time (T)/ Production (Q)	0.013	-0.012	-0.009	-0.021*
	(0.023)	(0.008)	(0.008)	(0.009)
Time (T)/Land (L)	-0.035	0.015	0.018	0.022
	(0.031)	(0.014)	(0.012)	(0.015)
Constant	-0.095	3.459**	11.011***	3.707**
	(8.620)	(1.136)	(1.411)	(1.354)