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Estimation of nitrous oxide (N_2O) emissions from agricultural soil management at higher resolution and implications for defining the cost of carbon at farm level

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Abstract

This paper aims to define a high-resolution model to estimate nitrous oxide (N_2O) emissions from the application of fertilisers to agricultural soils across the Republic of Ireland and to assess the implications for this approach on the assessment and mitigation of greenhouse gases (GHG) emissions. N_2O emissions from the management of agricultural soils represented 10% of the total national GHG emissions in 2020. The high-resolution model proposed here modifies the current methodology based on the Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) by adding soil characteristics and climate (environmental factors). To apply the high-resolution model, we use farm level microdata from the Teagasc National Farm Survey (NFS) and high-resolution spatial climate-based data over the 2014 to 2020 period. Results from the high-resolution model indicates a reduction of 3% in N_2O emissions compared to the baseline model (IPCC methodology). However, the difference in estimated N_2O emissions on individual farms can range from -45% to +40%. The carbon cost estimated by taking the high-resolution model results ranges from 20 to 150 euros per hectare, depending on local environmental factors. The design of a high-resolution emissions estimation process allows analysis of different agricultural practices and can assist in targeting appropriate GHG based mitigation measures based on cost-effectiveness criteria.

Keywords Nitrous oxide, environmental factors, carbon cost.

JEL code Q000

1. Introduction

Nitrous Oxide (N_2O) emissions from the management of agricultural soils represented 10% of the total national GHG emissions in 2020 in Ireland (Duffy et al., 2022). Under the Climate Action Bill (REF), Ireland has committed to reducing agricultural emissions by 25% by 2030 (GI, 2021). Therefore, efficient policy design dictated that this objective be achieved in the most effective way through implementing the approach mitigation measures. Carbon pricing is an instrument that captures the external costs of greenhouse gas (GHG) emissions and can reduce emissions from the agricultural sector in a cost-effective way. However, defining a carbon price requires an accurate quantification at farm level of N_2O emissions. The current methodology for quantifying N_2O emissions in the country uses a methodology based on the Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and national emissions factors differentiated by fertiliser type (Tier 2). Although this method approximates the sector's emissions, it does not consider two crucial environmental factors: soil characteristics (pH, texture, drainage) and climate (precipitation and temperature). By taking into account these factors, N_2O emissions can be quantified with increased granularity; consequently, economic measures such as carbon pricing at farm level can be estimated more accurately.

In this paper, we estimated the carbon cost from N_2O emissions using a high-resolution model to quantify N_2O emissions at farm level from 2024 to 2020 in Ireland. Additionally, we estimate a baseline model following the current methodology to quantify N_2O emissions (IPCC, 2006) to compare the effect to take into account the local environmental factors in the quantification of N_2O emissions. Our results show that the high-resolution model quantifies, on average, 3% fewer N_2O emissions than the baseline model. However, we found that the difference per farm ranges from -45% to 40%, indicating a substantial increase in the variability of N_2O emissions after applying the high-resolution model. The carbon cost estimated by taking the high-resolution model results ranges from 20 to 150 euros per hectare, depending on local environmental factors.

2. Methodology

2.1 High-resolution model

The high-resolution model proposed in this paper follows the IPCC methodology but includes the environmental factors that influence N_2O emissions. The high-resolution model is focused on modifying direct N_2O emissions for synthetic fertiliser and urine and dung inputs by adding soil characteristics (I_{SC}) and climate conditions (I_{CC}) using indices for each of them as follows:

$$EF_i \times I_{SC} \times I_{CC} \quad (1)$$

Where *EF* is the emission factor and *a* represents the synthetic fertiliser, urine, and dung. The soil characteristics index includes pH (I_{pH}), texture (I_{tem}), drainage (I_{dr}), soil type (I_{st}) and soil moisture (I_{sm}) as:

$$I_{SC} = I_{pH} \times I_{tex} \times I_{dr} \times I_{st} \times I_{sm} \quad (2)$$

On the other hand, the climate conditions index refers to annual precipitation (P_{ire}) and air temperature (A_{it}) as:

$$I_{CC} = I_{pre} \times I_{at} \quad (3)$$

The indices of soil characteristics are defined considering the information provided by previous research in Ireland and elsewhere to quantify EF around the application of N fertiliser and urine and dung inputs onto agricultural soils. The assumptions used for each soil and climate indices are described in Table 1. The indices allow capturing of the local environmental factors at the farm level. Therefore, the quantification of N_2O emissions has more granularity and it is more accurate.

Table 1. Soil and climate indices.

Soil characteristic	Assumptions	Reference
Soil pH (I_{pH})	Increase per unit pH: CAN = 1.1% UREA= 0.4% Reinput = 0.4% Urine and dung = 0.6%	Harty et al. (2016) Hafner et al. (2019) Krol et al. (2016) Marie et al. (2020) Murphy et al. (2022)
Soil texture (I_{tex})	Variation by texture type: Sandy loam = base category Clays = +5% Clays loam = +5% Sand = -5%	Harty et al. (2016) Krol et al. (2016)
Soil drainage (I_{dr})	Variation by drainage type: Good= base category Moderately= +10% Poorly= +20%	Harty et al. (2016) Roche et al. (2016) Rahman et al. (2021) Murphy e al. (2022)
Soil type (I_{st})	Variation by soil type: Organic=+10% Organic-mineral= base category	Harty et al. (2016) Roche et al. (2016) Rahman et al. (2021)

	Mineral=-10%	Murphy e al. (2022)
Soil moisture (I_{sm})	Increase 5% for 10% of m^3/m^{-3}:	Harty et al. (2016) Roche et al. (2016) Rahman et al. (2021) Murphy e al. (2022)
Climate variable	Assumptions	Reference
Annual precipitation	Increase 5% for 100 mm of water.	Harty et al. (2016) Roche et al. (2016) Rahman et al. (2021) Murphy e al. (2022)
Average annual Temperature	Increase 5% for every 5 ºC degree on difference between maximum and average temperature. $I_{at} = exp[0.21972225 * (T_{month} - T_{annual})]/3$	Misselbrook et al. (2006)

2.2 Baseline model

A baseline model was estimated to compare the results from the high-resolution model. The baseline model quantified N_2O emissions following the IPCC methodology accounting conventions and national emission factors as employed in the 2021 National Inventory Report for Ireland (Duffy et al., 2022). The model was designed to quantify N_2O emissions resulting from the application of manures and synthetic fertilisers to agricultural soils at the farm level, and the results are published in the Teagasc National Farm Survey 2020 Sustainability Report (Buckley, C. & Donnellan, T., 2021).

3. Data

3.1 Activity Data

This paper draws on Teagasc National Farm Survey (NFS) data from 2014 to 2020. This is a nationally representative sample of farming in Ireland based on farm size and system. The NFS is part of the EU Farm Accountancy Data Network and provides highly detailed activity data for 900 farmers annually, which are weighted to represent a total population of over 90,000 farms.

3.2 Soils data

The NFS includes data on the soil type of farms, which corresponds to the soil classification defined by Gardiner and Radford (1980). This classification includes 44 types of soils grouped into 10 great soil groups: podzols, brown podzolics, brown earths, grey brown podzolics, blanket Peats, gleys, basin peats, rendzinas, and lithosols. The group classification identifies the main natural soil characteristics required to apply the high-resolution model: 1) pH level, 2) texture, 3) drainage and 4) soil type.

Table **2** shows the distribution of farms for the categories used in the soil indices previously described by year. The farms included in the NFS have the following main characteristics: around 51% of farms have organic-mineral soil, 35% have soil pH between 5.3 to 5.5, 35% of farms have a texture loam, and 50% of farms have well drained soil.

Table 2. Percentage distribution of farms in the NFS by soil characteristics and year.

Soil characteristic	2014	2015	2016	2017	2018	2019	2020
Type soil							
Mineral	33.5	34	35.3	34.9	34.9	34.8	34.4
Organic	14.6	15.9	13.8	14	13.6	13.9	14.9
Organic-Mineral	51.9	50.1	51	51.1	51.6	51.3	50.7
Total	100	100	100	100	100	100	100
Soil pH							
<4.9	21.2	20.7	18.7	17.5	16.7	17.4	16.8
4.9-5.2	6.5	5.9	6.7	6.3	6.5	5.8	5.5
5.3-5.5	31.5	32.1	33.8	37.3	37.8	39.6	40
5.6-5.8	5.3	6.5	6.4	6.2	6.2	5.7	5.5
5.9-6.2	12.2	11.7	12.1	12.2	12.1	12.1	12.6
6.3-6.5	3.2	5.1	3	2.5	2.3	1.7	1.7
6.5<	20	18	19.3	18	18.5	17.6	17.8
Total	100	100	100	100	100	100	100
Soil Texture							
Clay	9.6	11.1	9.7	9.4	9.4	9.4	10
Clay loam	18.8	17.9	19	18.3	18.4	18	18.5
Loam	34.2	34.9	33.3	34.9	35.2	35.2	36.7
Sand	2.7	2.7	2.9	3	3.4	3.2	3.5
Sandy loam	34.6	33.4	35.1	34.4	33.6	34.2	31.3
Total	100	100	100	100	100	100	100
Soil Drainage							

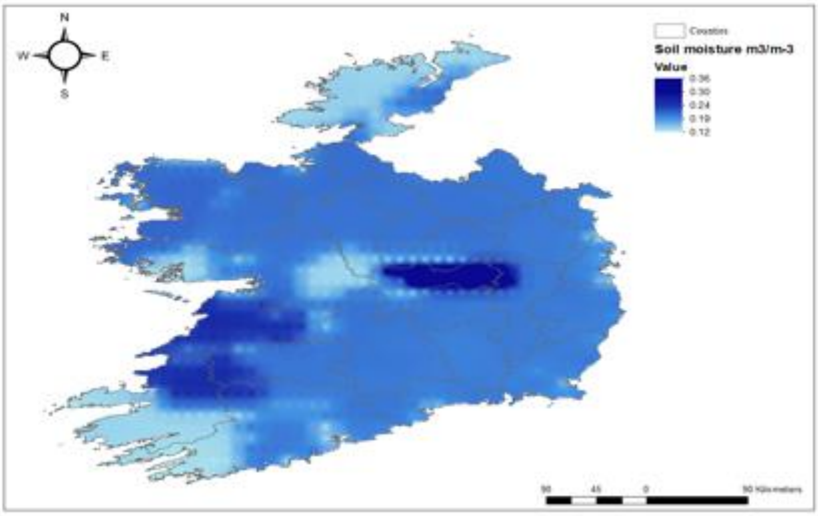
Soil characteristic	2014	2015	2016	2017	2018	2019	2020
Moderately	21	21.7	19.7	18.9	18.5	18.3	17.8
Poorly	32.9	33.4	33.1	32.6	32.2	31.6	32.1
Well	46.1	44.8	47.1	48.5	49.3	50.1	50.2
Total	100	100	100	100	100	100	100
Soil moisture							
0 - 10	5.27	3.19	4.92	5.47	5.20	4.71	7.64
11 - 20	12.70	12.85	12.51	11.50	12.20	11.03	7.39
21- 30	77.93	80.16	78.77	79.80	78.20	80.69	80.42
31 - 45	4.09	3.80	3.80	3.24	4.40	3.56	4.56
Total	100	100	100	100	100	100	100

Note: The values are weighting according to their representativeness by year.

3.3 Climate data

The farmers within the Teagasc NFS have a spatial reference, a georeferenced point where the farm's land is located. This georeferenced is a proxy point that allows overlaying of the information on climate conditions based on climate data rasters obtained from the Met Éireann project (Gleeson et al., 2017). The climate data is based on high-resolution (2.5 km horizontal grid) data for Ireland. The data obtained from this source are 1) soil moisture, 2) annual precipitation, and 3) air temperature. The climate data shows considerable differences among regions in the country. Figure 1 shows the soil moisture map, which measures the percentage of water per cubic meter of land (m^3/m-3). The border, midlands and west regions have more humidity in the soils than the south and east regions.

Figure 1. Soil moisture levels in Ireland, 2020.

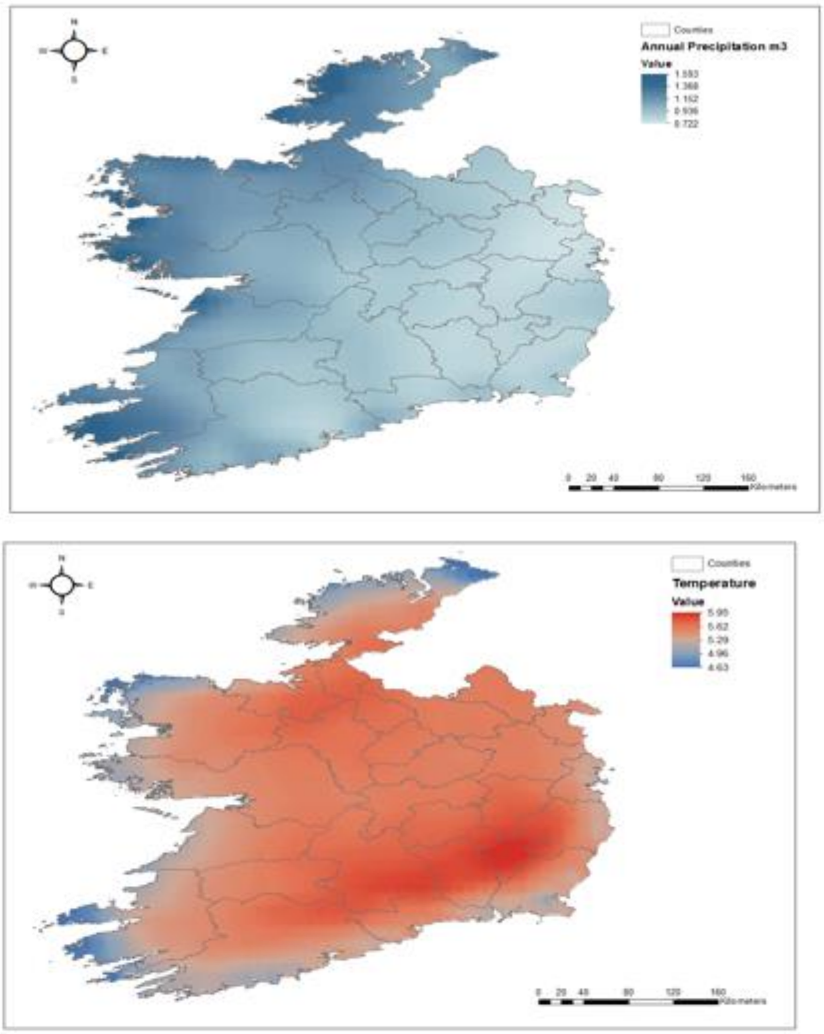


Note: Data from Met Éireann (Gleeson et al., 2017) at 2.5 km grid spacing. Soil moisture accumulation was measured as a percentage of cubic meters of water m^3/m-3.

On the other hand, Figure 2 shows the annual precipitation and the difference between the highest and annual average temperature. The south-west and north-west regions have higher precipitation levels, above 1.1 m^3 of water per year, while the east region has lower precipitation levels, under 1 m^3 of water per year. Regardless of the air temperature, the highest air temperature variability is recorded in the centre and south regions of the country. The average temperature difference in these regions ranges from 6 to 8 ºC degrees, whereas for land boundaries with the sea, the difference is 5 ºC degrees on average per year.

Figure 2. (a) Annual precipitation and (b) difference between highest and annual average temperature in Ireland, 2020.

(a)



(b)

Source: Data from Met Éireann (Gleeson et al., 2017) at 2.5 km grid spacing. (a) The annual precipitation is measured as cubic meters of water (m^3 of water). (b) The difference between the highest and annual average air temperature in Celsius degree (ºC).

4. Results

4.1 Baseline model

The results obtained for applying the baseline model are presented in Table 3. This shows total N_2O emissions and the distribution by soil type. The baseline model quantifies 4,359 kt of N_2O emissions for 2020 for Ireland, this value represents around 80% of N_2O emissions reported in national inventories. The difference is because NFS does not include all farm types, as well as small farms. These are mainly released from organic-mineral soils, which concentrate 52% of emissions, whereas 36% of the emissions are emitted from mineral soils. Over the period analysed, the N_2O emissions from mineral and organic soils has been increased.

Table 3. N_2O emissions and percentage distribution of farms by soil type, 2014-2020.

Year	Mineral		Organic		Organic-Mineral		Total	
	N_20 emissions (KT CO_2 eq)	%	N_20 emissions (KT CO_2 eq)	%	N_20 emissions (KT CO_2 eq)	%	N_20 emissions (KT CO_2 eq)	%
2014	1,515.2	34.9	484.3	11.2	2,341.0	53.9	4,340.6	100.0
2015	1,398.7	37.4	416.7	11.1	1,924.5	51.5	3,740.0	100.0
2016	1,443.6	36.7	407.9	10.4	2,084.5	53.0	3,936.0	100.0
2017	1,659.5	36.6	514.3	11.3	2,361.6	52.1	4,535.4	100.0
2018	1,855.8	37.5	529.3	10.7	2,561.4	51.8	4,946.5	100.0
2019	1,684.2	37.4	517.8	11.5	2,306.9	51.2	4,509.0	100.0
2020	1,560.2	35.9	532.1	12.2	2,258.2	51.9	4,350.5	100.0

3.1 High-resolution model

The high-resolution model aims to estimate emissions accounting for environmental factors. This is the main change compared to the baseline model, which only considers the total amount of inputs applied and assumes standard environmental conditions. Table 4 presents the overall results of N_2O emissions from managed soils using the higher-resolution and baseline model. The high-resolution model quantifies fewer emissions than the baseline model; the difference is 3% on average, although it is higher in the years 2016 and 2017.

Table 4. N_2O emissions by high-resolution and baseline model, 2014-2020

Year	Baseline Model (KT CO_2 eq)	High-Resolution Model (KT CO_2 eq)	Difference (%)
2014	4,340.55	4,179.84	-3.70
2015	3,739.97	3,582.27	-4.22
2016	3,936.01	3,708.57	-5.78
2017	4,535.36	4,264.67	-5.97
2018	4,946.53	4,774.53	-3.48
2019	4,509.00	4,313.36	-4.34
2020	4,350.50	4,220.75	-2.98

Analysing the results at farm level (See Table 5), we find a similar pattern to the total N_2O emissions. According to the high-resolution model, a farm emitted, on average, 50.6 ton of N_2O emissions in 2020. The difference between the high-resolution model and the base model at this level is on averages 3%. However, we found that the difference per farm ranges from -45% to 40%, indicating a substantial increase in the variability of N_2O emissions after applying the high-resolution model.

Table 5. N_2O emissions per farm by high-resolution and baseline model, 2014-2020.

Year	Baseline Model (Ton CO_2 eq)	High-Resolution Model (Ton CO_2 eq)	Difference (%)
2014	49.71	47.87	-2.36
2015	52.25	50.05	-3.76
2016	47.47	44.73	-4.85
2017	50.86	47.82	-4.72
2018	56.36	54.40	-3.27
2019	52.81	50.52	-3.20
2020	52.20	50.64	-1.55

The high-resolution model shows greater variability than the baseline model, particularly when analysing the results by hectare and type of farm (See Table 6). Dairy farms are the highest emitters of N_2O emissions, around 2 tons of N_2O emissions per hectare, and cattle farms are the lowest emitters, less than 1 tons N_2O emissions per hectare. However, tillage farms are the ones who show the biggest reduction on average in N_2O emissions after applying the high-resolution model.

Table 6. N_2O emissions per hectare and farm type by high-resolution and baseline model, 2014-2020.

Baseline model
N_2O emissions per hectare (Ton CO_2 eq)

Year	Dairy	Cattle rearing	Cattle other	Sheep	Tillage
2014	1.86	0.81	0.96	1.03	1.11
2015	1.84	0.76	0.94	0.97	1.14
2016	1.84	0.83	1.02	1.00	1.05
2017	1.93	0.89	0.98	1.07	1.01
2018	2.05	0.95	1.07	1.10	1.16
2019	1.93	0.88	0.95	0.98	1.05
2020	1.90	0.88	0.97	0.99	1.05

High-Resolution model
N_2O emissions per hectare (Ton CO_2 eq)

Year	Dairy	Cattle rearing	Cattle other	Sheep	Tillage
2014	1.80	0.79	0.95	0.97	1.02
2015	1.75	0.74	0.90	0.92	1.09
2016	1.72	0.81	0.96	0.94	0.98
2017	1.80	0.86	0.94	0.98	0.93
2018	1.98	0.94	1.06	1.00	1.07
2019	1.83	0.86	0.92	0.96	0.99
2020	1.84	0.87	0.94	0.98	1.02

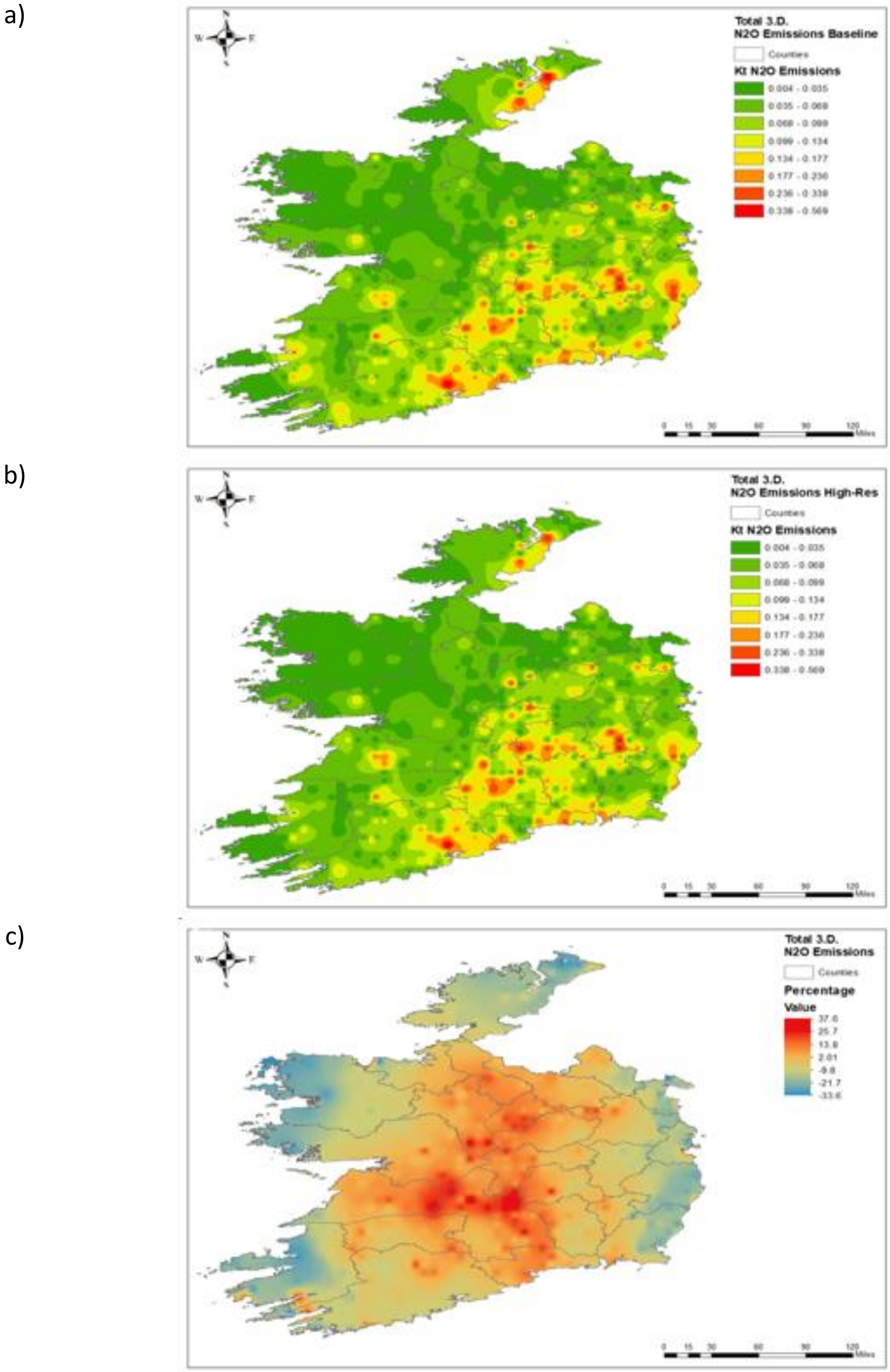
Difference between High-Resolution and Baseline model
Percentage

	Dairy	Cattle rearing	Cattle other	Sheep	Tillage
2014	-2.71	-0.45	-0.55	-5.15	-8.06
2015	-4.89	-2.28	-4.01	-4.27	-3.94
2016	-6.56	-3.42	-4.41	-6.02	-5.63
2017	-6.21	-3.01	-3.12	-7.41	-8.30
2018	-2.95	-1.21	-0.97	-9.38	-7.63
2019	-4.98	-1.76	-3.43	-1.91	-5.27
2020	-2.92	-0.30	-2.28	-0.14	-3.71

The differences between the baseline and high-resolution models are spatially heterogeneous due to the local soil characteristics and climate conditions. Figure 3 shows the results after applying the baseline and high-resolution models and the difference between models. According to the baseline model, N_2O emissions are higher in the middle and south regions of

Ireland. After applying the high-resolution model, these regions continue to be the regions with the highest emissions.

Figure 3. Results after applying the a) baseline approach, b) high-resolution model (in Kt N_2O), and c) difference between models (in percentage), 2020.



3.2 Effect of soil characteristics and climate on N_2O emissions

Regression analysis was used to measure the impact of soil characteristics and climate on the difference in the estimated N_2O emissions between the baseline and high-resolution models. The estimation was a quantile regression that is appropriate to model a distribution such as N_2O emissions because the high-resolution model assumes that emissions depend on different factors interacting with each other; consequently, it is a non-linear and multidimensional variable which can be overestimated or underestimated by linear regression (Angrist & Pischke, 2009). The dependent variable in the model was the natural logarithm of the difference of N_2O between the baseline and high-resolution models. The covariables were the soil characteristics and climate variables used in the high-resolution model. In addition, the estimation includes variables for the farm size and gross output per hectare in order to control for possible effects related to the management of farms. **Table 7** shows the quantile regression results.

Table 7. Quantile regression results

	Quantiles				
Variable	0.15	0.25	0.5	0.75	0.85
Soil pH	0.008*** (0.001)	0.008*** (0.001)	0.007*** (0.001)	0.006*** (0.001)	0.006*** (0.001)
Soil drainage					
Moderately	0.010 (0.007)	0.007 (0.005)	0.007* (0.004)	0.006* (0.003)	0.006 (0.003)
Poorly	0.042*** (0.008)	0.037*** (0.006)	0.037*** (0.004)	0.028*** (0.004)	0.029*** (0.004)
Soil texture					
Clay	0.011 (0.016)	0.014 (0.013)	0.022* (0.010)	0.016** (0.006)	0.015 (0.009)
Clay loam	0.019 (0.013)	0.019* (0.008)	0.027*** (0.006)	0.030*** (0.005)	0.034*** (0.005)
Loam	0.022 (0.012)	0.023*** (0.007)	0.030*** (0.005)	0.023*** (0.004)	0.027*** (0.005)
Sandy loam	-0.005 (0.011)	-0.001 (0.007)	0.003 (0.006)	-0.001 (0.004)	0.000 (0.005)
Soil type					
Mineral	-0.028*** (0.008)	-0.018** (0.006)	-0.020*** (0.003)	-0.012*** (0.003)	-0.015*** (0.004)
Organic	0.013 (0.007)	0.019*** (0.005)	0.025*** (0.007)	0.031*** (0.004)	0.035*** (0.008)
Soil moisture	0.035* (0.015)	0.041** (0.014)	0.044*** (0.010)	0.053*** (0.013)	0.063*** (0.017)
Annual precipitation	0.047*** (0.009)	0.054*** (0.006)	0.051*** (0.005)	0.040*** (0.004)	0.032*** (0.004)

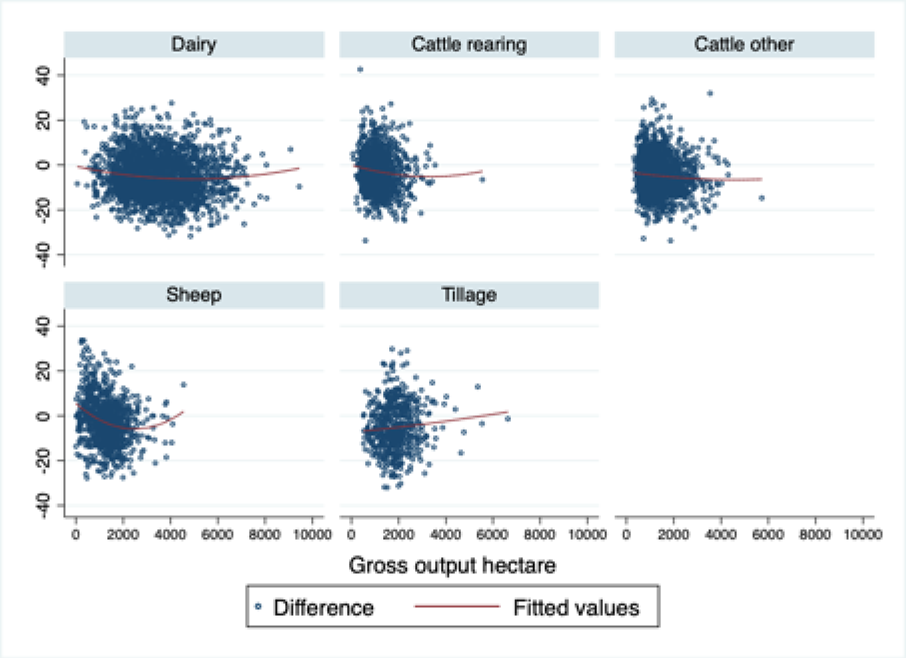
	Quantiles				
Variable	0.15	0.25	0.5	0.75	0.85
Temperature (Difference max-average)	0.149***	0.164***	0.138***	0.174***	0.237***
	(0.047)	(0.037)	(0.029)	(0.020)	(0.020)
Gross output €					
1,000 – 3,000	-0.001	0.000	-0.003	-0.003	-0.003
	(0.004)	(0.003)	(0.003)	(0.002)	(0.003)
> 3,000	-0.047***	-0.027***	-0.017***	-0.010***	-0.011***
	(0.011)	(0.007)	(0.004)	(0.003)	(0.003)
Farm size ha					
30 -75	-0.003	-0.004	-0.002	-0.000	0.000
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
More 75	-0.100***	-0.068***	-0.020***	-0.009*	0.003
	(0.017)	(0.013)	(0.005)	(0.003)	(0.007)
Constant	4.163***	4.117***	4.177***	4.334***	4.418***
	(0.108)	(0.085)	(0.065)	(0.043)	(0.042)
R-squared	0.4363	0.3988	0.3246	0.3002	0.3131
N	837	837	837	837	837

According to the results of the estimation, the local climate generates a variation in N_2O emissions, which goes from 15% to 27%, where the difference between the highest and annual average temperature is the most relevant variable. On the other hand, the effect of different soil characteristics was responsible for a range from 5% to 15% in N_2O emissions variability, and soil moisture is the variable more important. This means that the application of one kilo of N input in different parts of the country generates different levels of N_2O emissions, which depend on the local environmental and biophysical conditions that can affect the nitrification and denitrification process.

3.3 Carbon cost estimation

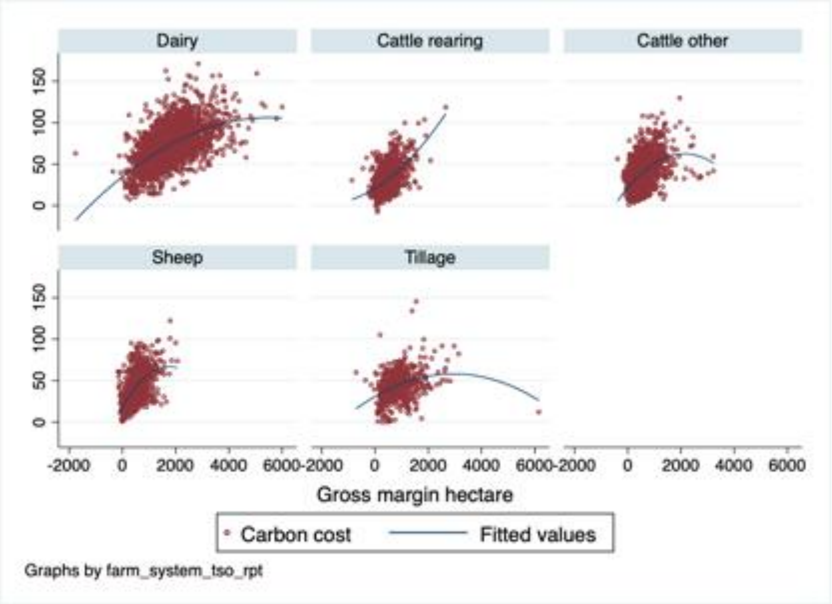
A carbon cost value was estimated from the results obtained, using as a reference value of 41 euros per tonne of CO_2, which is the current value in Ireland for the transport and electricity sectors (GI, 2022). Figure 1 shows the difference in the carbon cost between the high-resolution and baseline model relative to the gross output per hectare by type of farm. There are farms that have reduced the carbon cost by 30%, and farms that have increased the carbon cost by 20% after applying the high-resolution model. The difference can be a redistribution effect of environmental factors.

Figure 4. Difference of the carbon cost between high-resolution and baseline model by farm type, 2014-2020.



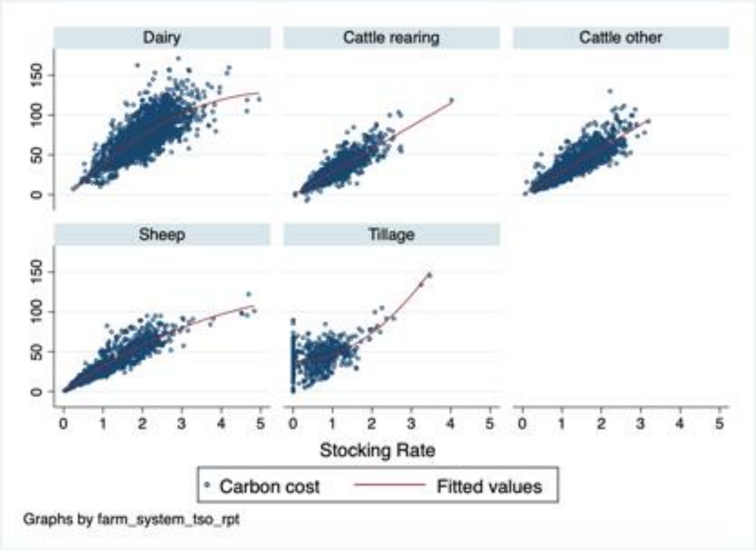
The carbon cost estimated using the high-resolution model is shown in Figure **5**. The value of the carbon cost depends on the amount of input applied to soils and local environmental factors. The farms with the highest cost of carbon from N_2O per hectare are the Dairy farms. The average carbon cost is 74 euros. However, the carbon cost for some dairy farms is higher than 100 euros, specifically, in the farms with the highest gross output per hectare. Cattle, sheep and tillage farms have, on average, a carbon cost of 40 euros per hectare, and it is related to the gross output per hectare, in addition to the local environmental factors.

Figure 5. Carbon cost and gross margin per hectare by farm type, 2014-2020.



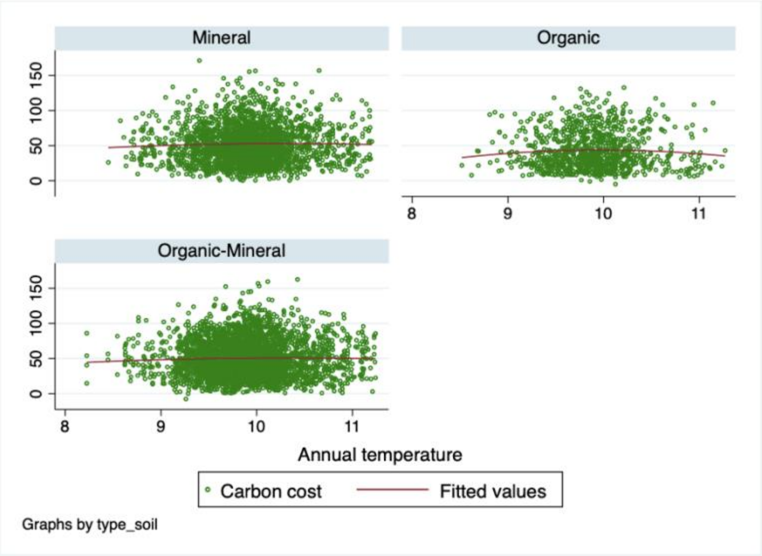
Furthermore, The carbon cost has a positive relationship with the stoking rate (see **Figure 6**). Dairy farms have the highest value of this indicator, 3 animals per hectare in average. Cattel farms have a high value of stoking rate and a positive relationship with the carbon cost estimated.

Figure 6. Carbon cost and stoking rate per hectare by farm type, 2014-2020.



The carbon cost estimated with the high-resolution model shows that the main environmental factors are soil moisture, soil type, and temperature levels. **Figure 7** shows the carbon cost relating to temperature by soil type. The highest carbon cost is recorded in places with higher temperatures and organic-mineral soils.

Figure 7. Carbon cost from the high-resolution model by soil type, 2014-2020.



5. Discussion and Conclusion

The findings of this study suggest that local environmental factors are essential in quantifying N_2O emissions at farm level. The local climate generates a variation in N_2O emissions, which goes from 10% to 27%, while the effect of different soil characteristics was responsible for a range from 5% to 15% in N_2O emissions variability. Hence, the quantification of the N_2O emissions at farm level improves after applying the high-resolution model, and it has an effect on the estimation of the carbon cost at farm level. Some farms have reduced the carbon cost by 30%, and other farms have increased the carbon cost by 20% with the high-resolution model. Furthermore, the carbon cost estimated by taking the high-resolution model results ranges from 20 to 150 euros per hectare. The carbon cost estimated in this paper takes into account the spatial heterogeneity and cost-efficacy criteria, and it could be more efficient to quantify the N_2O emission at farm level than the estimated carbon cost estimated with the baseline model.

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