sustainability

MDPI

Article

A Business Case for Climate Neutrality in Pasture-Based Dairy Production Systems in Ireland: Evidence from Farm Zero C

Theresa Rubhara [1,*], James Gaffey [1,2,*], Gavin Hunt [2], Fionnuala Murphy [2,3], Kevin O'Connor [2,4], Enda Buckley [5] and Luis Alejandro Vergara [2,3]

1 Circular Bioeconomy Research Group, Munster Technological University, V92 HD4V Tralee, Ireland
2 BiOrbic Bioeconomy SFI Research Centre, University College Dublin, Belfield, D04 V1W8 Dublin, Ireland; gavin.hunt@biorbic.com (G.H.); fionnuala.murphy@ucd.ie (F.M.); kevin.oconnor@ucd.ie (K.O.); luis.vergara@ucdconnect.ie (L.A.V.)
3 School of Biosystems and Food Engineering, University College Dublin, Belfield, D04 V1W8 Dublin, Ireland
4 School of Biomolecular and Biomedical Science, University College Dublin, Belfield, D04 V1W8 Dublin, Ireland
5 Carbery Group, Ballineen Co., P47 YW77 Cork, Ireland
* Correspondence: theresarubhara@gmail.com (T.R.); james.gaffey@mtu.ie (J.G.)

Abstract: Agriculture in Ireland is responsible for producing and exporting healthy, nutritional food pivotal for meeting the Sustainable Development Goals (SDGs) such as global food security, economic development and sustainable communities. However, the agricultural sector, dominated by a large bovine population, faces the challenge of reducing greenhouse gas (GHG) emissions to reach climate neutrality by 2050. The objective of the current study was to model the environmental and economic impact of simultaneously applying farm-level climate change mitigation strategies for a conventional grass-based dairy farm in Ireland. An average farm of 52 ha with a spring-calving herd of 93 was used as a reference scenario to create a business case. Partial budgeting was used to calculate the annual net benefit. A cradle-to-grave life cycle assessment (LCA) was used to model the reduction in GHG emissions, which was expressed as kg of carbon dioxide equivalent per kilogram of fat- and protein-corrected milk (kg CO_2-eq/kg FPCM). The baseline for average emissions was 0.960 kg CO_2-eq/kg FPCM. An average farm would reduce its annual emissions by 12% to 0.847 kg CO_2-eq/kg FPCM in Scenario 1, where climate change mitigation strategies were applied on a minimal scale. For Scenario 2, the emissions are reduced by 36% to 0.614 kg CO_2-eq/kg FPCM. In terms of annual savings on cash income, an increase of EUR 6634 and EUR 18,045 in net savings for the farm are realised in Scenarios 1 and 2, respectively. The business case provides evidence that farms can move towards climate neutrality while still remaining economically sustainable.

Keywords: climate-neutral agriculture; greenhouse gases; net benefit; global warming

check for updates

Citation: Rubhara, T.; Gaffey, J.; Hunt, G.; Murphy, F.; O'Connor, K.; Buckley, E.; Vergara, L.A. A Business Case for Climate Neutrality in Pasture-Based Dairy Production Systems in Ireland: Evidence from Farm Zero C. *Sustainability* **2024**, *16*, 1028. https://doi.org/10.3390/su16031028

Academic Editors: Manoj Kumar Nallapaneni, Idiano D'Adamo and Massimo Gastaldi

Received: 28 November 2023
Revised: 15 January 2024
Accepted: 16 January 2024
Published: 25 January 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Irish agriculture has the potential to become a global leader in sustainable food systems through the production, marketing and management of low-carbon food. According to Ireland's Department of Agriculture, Food and the Marine [1], the agricultural sector contributed 9.5% of Irish merchandising exports and approximately EUR 18.7 billion to the value of agri-food exports in 2022. The sector underpins much of rural Ireland, with over 170,400 (7.1% of total employment) people employed in the agri-food sector [1]. Ireland exports 90% of its food products to 160 countries worldwide, contributing directly to the Sustainable Development Goal (SDG) of global food security (SDG2) and economic development [1]. Despite such a positive economic contribution, the agricultural sector, is, however, associated with negative environmental impacts, such as greenhouse gas (GHG) emissions, loss of natural habitats and diversity due to intensive agriculture and monoculture, a decline in air and water quality and deforestation. This poses a threat to the achievement of the SDG13, SDG14 and SDG15 targets of ensuring environmental sustainability. As consumers become more aware of the various production systems and how their consumer choices can have an impact on the environment [2], the demand for products that are sustainably produced will continue to increase. Farmers could integrate greater innovation in the production of food products to ensure that food is produced in an environmentally sustainable manner. Currently, Ireland produces approximately 1.1 million tonnes of food waste each year, which results in a carbon footprint of 3.6 Mt CO_2eq [3]. As such, increasing production to feed the world, is not, in and of itself, sustainable. It should be noted that the SDGs towards sustainability, previously listed, are all interlinked and not always antagonistic. For instance, with responsible production and consumption (SDG12), food losses can be minimized, natural resources less depleted and greater food security can be achieved [4].

Unlike other European countries where transport and energy industries are the major GHG emitters, in Ireland, agriculture accounted for about 37.5% of the nation's total GHG emissions in 2021 [5], approximately double the emissions from the energy industry. The fact that agriculture continues to contribute the largest sectoral percentage of GHG emissions to the national inventory is a major cause for concern for such an important industry. Ireland has regularly fallen short of its climate change emission targets and currently faces a very challenging target of reducing overall emissions by 51% by 2030 and achieving net zero emissions by 2050 [6,7]. The largest share of GHG emissions in Irish agriculture relates to ruminant production and is predominantly a result of rumen methane and nitrous oxide from soils. The 2021 Irish Farm Sustainability Report [8] indicated that the amount of GHG emissions from an average Irish farm rose in 2020, largely due to an increase in herd size, in addition to a 3.3% and 6.2% increase in fertiliser use and liming, respectively [5].

With over 80% of the agricultural land in Ireland being grassland [9], the grass-based nature of livestock production in the country offers positive environmental opportunities in terms of manure recycling, the integration of livestock and crops for feed, low feed–food competition, biodiversity, soil quality and organic carbon content [10]. Grass, a relatively cheap but abundant feed source, also gives Irish dairy farmers a competitive edge in terms of lower costs and higher profits [11]. Results from the National Farm Survey (NFS) [12] show that dairy remains the most economically and socially sustainable farming system in Ireland; however, the continuous expansion of the bovine population has resulted in higher agricultural GHG at the national level due to higher methane emissions. Ireland aims to achieve a climate-neutral food system by 2050 [13]. Climate-neutral agriculture is defined as net zero emissions of agricultural GHG emissions, implying that the total GHGs (expressed in the carbon dioxide equivalent) released into the atmosphere by sources are equal to or less than the carbon absorbed by carbon sinks [14,15]. In grass-fed systems like Ireland, such as Australia [16–18] and New Zealand [19], much of the research towards climate-neutral agriculture has put a major emphasis on carbon sequestration modelling or strategies that require major land use changes and capital investment. To reduce emissions in agriculture, robust but practical measures are required to be implemented at the farm level. In previous research in Ireland, strategies such as clover, multispecies swards, slurry management and the use of protected urea have shown positive environmental impacts [20–22]. However, such research and analyses of the impact of the mitigation strategies have largely been conducted in isolation. In contrast, the Farm Zero C (FZC) initiative, which is the basis for the current paper, combines at least 15 strategies at once. FZC uses a holistic and pragmatic approach to transform a conventional farm into a more sustainable farm, with the overall aim of achieving a climate-neutral dairy farm. To achieve this, FZC undertakes an interdisciplinary program of work to reduce emissions, targeting several areas:

I. Soil and grassland management: measuring and increasing soil carbon organic stocks through soil and grassland management practices such as incorporating clover and growing multispecies swards;

II. Animal diet and breeding: trialling different types of diets and anti-methane additives that can alter animal digestion, reducing the amount of methane emitted by cows;
III. Renewable energy: producing and using renewable energy on the farm where possible to reduce the farm's reliance on carbon-emitting fossil fuels.

The research completed to date has demonstrated that the combined strategies can significantly reduce the emissions at Farm Zero C as the life cycle assessment (LCA) modelling of GHG emissions has shown a decrease in emissions from 0.86 kg CO_2-eq/kg FPCM in 2018 to 0.66 kg CO_2-eq/kg FPCM in 2022. Previous studies have shown that adoption decisions for climate change mitigation practices among farmers are not based solely on the environmental impact of the strategies [23]. Farmers are likely to adopt innovations which they perceive to have economic returns [24]; for instance, those arising from increased efficiencies, economies of scale and financial incentives [23]. Various economic-oriented studies have been published focusing on the costs of climate change mitigation in Ireland; however, most of these either used input-output models or policy analysis to provide a broad perspective on the economic impacts of climate change mitigation at the national or regional level [25,26]. For instance, The Irish Marginal Abatement Cost Curve (MACC) study provides a detailed cost analysis of the climate mitigation strategies across all farming systems with the absolute emission reduction pathways at the national level [26]. This current paper, on the other hand, builds on data arising from Farm Zero C combined with available information on climate change mitigation costs to provide a case study on how a combination of strategies can be applied for economic and environmental sustainability at the farm level. A business case, based on the implementation of a selection of the Farm Zero C climate-neutral strategies, is modelled under specified assumptions to determine the economic and environmental impact of a set of mitigation measures applied at different levels. The objective of this paper is to provide evidence that climate neutrality at the farm level produces opportunities for cost reduction and revenue growth, thus contributing positively to SDG13's targets of combating climate change.

2. Materials and Methods

2.1. Description of the Farm

A case study dairy farm in Ireland which closely resembles an average Irish dairy farm adopted from the National Farm survey data and agricultural factsheet [1,12] was used for formulating the Holistic FZC business case scenarios. The business case assumes that the case study farm reduces its emissions to a certain level year on year until it reaches climate neutrality by 2050. The physical farm components are important for evaluating the economic and environmental analysis and these are summarized in Table 1 below. An average dairy farm of 52 ha located in the southern part of Ireland stocked at 2.2 LU/ha, which currently uses none of the FZC climate mitigation strategies is presented as the baseline scenario. This represents a typical Irish pasture-based, spring-calving dairy farm where cows spend an average of 241 days on grass.

Table 1. Values used to describe case study farm.

Variable	Description
Farm Size	52 ha
Soil drainage	Average
Herd size	93 dairy cows
Replacement rate	22%
Productivity	5700 L/cow/yr @4.21% fat and 3.57% protein KG MS/Cow—455

Table 1. *Cont.*

Variable	Description
Chemical nitrogen fertiliser use	220 kg/ha (50% Urea & 50% CAN)
Concentrate	1100 kg/cow/yr
Grazing management	241 days per annum
Animals culled	20 Mature heads @ 550 kg live weight
Slurry spreading method	Splash plate
Slurry spreading season	50% in Summer 50% in Spring
Manure storage	Pit storage for the mature herd and heifers, solid storage for calves

2.2. Mitigation Measure Selection

Since June 2021, the FZC holistic climate-neutral strategies have been tested and demonstrated on a commercial dairy farm, Shinagh Farm, at Bandon, Co., Cork, Ireland. The selected mitigation strategies, for the current business case, were based on the findings from these research, demonstration and analysis activities. Table 2 presents a summary of the assumptions made, and economic and environmental impacts based on evidence from the FZC trials and other research outcomes. It should be noted that Shinagh farm is not representative of the conventional farm in Ireland, as it is highly resource efficient with a relatively low carbon footprint of 0.66 kg CO_2-eq/kg FPCM as compared to 0.96 kg CO_2-eq/kg FPCM for an average farm in 2022.

The information in Table 2 includes all trials and strategies implemented at FZC except for green biorefinery and soil carbon sequestration. Holistic livestock management strategies which have been shown to increase technical efficiencies including maximizing utilisation of grass, improving grassland management by incorporating clover and MSS, optimising slurry for organic nitrogen, and improving the economic breeding index were implemented based on previous trials, and assumptions were made based on this work [22,27,28]. Innovative technologies such as feed and slurry additives were trialled at FZC and the results were used to model the conventional farm. The strategies were chosen on the basis that they are both practical to implement in the short run and effective in reducing GHG emissions. Whilst the use of the green biorefinery for grass has demonstrated a high potential for reducing emissions from imported feed, it may be more challenging to implement in the short term, as proper planning is required to address issues relating to the initial investment cost and the ownership of equipment [29]. One option would be for farmers to come together as a cooperative and purchase a biorefinery where they would process their own grass. Similarly, without evidence-based measurement, reporting and verification (MRV) of carbon sequestration it is difficult to model the level of soil organic carbon and the associated costs [30]. The FZC is taking steps to implement MRV, but more data are required to include it in the model.

The mitigation measures included were aimed at reducing emissions per unit of output (CO_2-eq/kg FPCM), rather than absolute farm emissions. This approach allows the inclusion of strategies which increase production and sometimes the farm's emissions such as the economic breeding index (EBI) and extending the grazing season but significantly reduce emissions per kg of product [31]. Where available, costs of inputs such as fertiliser were adopted from the central statistics office; however, for novel technologies such as feed and slurry additives which are not readily available on the market, the FZC prices were used, which may be more or less the same as commercial prices.

Table 2. Summary of mitigation strategies and assumptions.

Strategy	Target Emission Source	Environmental Impacts	Economic Impacts	Assumptions
Reduce chemical N use through White clover, Red clover and Multispecies swards	Fertiliser use	Reduces nitrous oxide emissions and nitrate losses to water Reduces the upstream impacts associated with fertiliser production	Reduction of fertiliser costs Incremental reseeding costs	Nitrogen fertiliser reduction to 150 kg/ha [22] No changes to Dry Matter (DM) yield [21,32]
Grazing management	Manure management	Manure left on pasture which has lower methane emissions than stored [33]	Savings from less silage and less concentrate feed Higher milk solids	Farmer either reduces concentrate or increases productivity An extra week on grass reduces total GHG by 1% [31]
Protected Urea	Fertiliser use	Reduces N_2O and NH_3 losses [20]	Protected urea is cheaper per kg N than calcium ammonium nitrate (CAN) though slightly more expensive than urea	Cost is based on nitrogen value only; phosphorous (P) and potassium (k) costs remain constant
Slurry management through: Spreading all slurry in Spring Use of Low Emission Slurry Spreading (LESS) Chemically amend slurry	Manure management	Spreading slurry in Spring ensures less N is lost as NH_3 Reduces N losses through NH_3 Reduces ammonia and methane emissions during slurry storage slurry	Approximately 0.4 kgN/m^3 more is saved in Spring than in Summer thus reducing total fertiliser costs [34] Reduces demand for chemical fertiliser thus reducing N_2O losses [34] The extra cost of the chemical amendment	The value of N retained only is considered, P&K values remain constant Extra spreading cost EUR 20/h when LESS is used instead of Splash plate, assuming splash plate spreads @ 34 m^3/h and trailing shoe @ 28 m^3/h [27,35] Chemical amendment cost was estimated at EUR 2/m^3 slurry (estimates from FZC trials)
Use native feeds	Feed production	Reduces GHG emissions associated with imported soya and grain	The cost of native ingredients is higher than conventional feed	Native feeds cost EUR 25 more per tonne than conventional feeds (estimates from FZC)
Anti-methane additives (Bovaer)	Animal digestion	Reduces CH_4 emissions	The extra cost of the dietary additive	Dietary additives cost approximately EUR 75/cow/yr (estimates from FZC) Milk yield remains constant
Reduce replacement rate	All hotspots		Costs are reduced as the farmer has less young stock to rear	Rearing a heifer from the calf for 24 months costs approximately EUR 1500 [36]
Use renewable sources to reduce energy inputs	Farm Energy	Reduces CO_2 emissions	Investment costs for the renewable energy equipment	Potential savings or costs were not included in the analysis as they represent an investment cost which differs across different technologies
Increase productivity by 5% (EBI and management)	All hotspots	For every EUR 10 increase in EBI, GHG emissions decline by 1% per unit of product [28]	Increases farm revenue from sales of extra milk solids	The total farm, emissions do not decrease but as productivity increases the quantity of GHG per kg of FPCM reduces

2.3. Modelling Different Scenarios

Two scenarios were used to model the likely impacts of different levels of application for several mitigation strategies when applied simultaneously. Scenario 1 (S1) represents the minimal implementation case option which includes strategies that can be implemented in the short term at a low scale without major costs (low-hanging fruit) usually adopted by the risk-averse farmers, as shown in Table 3. These include reducing fertiliser use, incorporating clover and MSS in grasslands, slurry management, and reducing feed concentrate and replacement rate. Reducing chemical fertiliser use and switching to protected urea has been estimated to reduce nitrous oxide emissions by 5.4% for the Irish agricultural sector in the MACC [35]. However, reducing the quantity of chemical fertiliser on its own can result in low productivity and creates a risk of the grassland being less self-sufficient to feed the animals [37]. White clover incorporation in grassland has been shown to reduce chemical fertiliser requirement to 150 kg/ha [22,38,39] and using red clover in silage can completely replace chemical fertiliser requirements [32]. The modelling for the FZC business case considered the area required for grass-clover swards and MSS to maintain sward productivity, which would result in a 16% and 46% reduction in fertiliser use for S1 and S2, respectively, as shown in Table 3. Scenario 2 (S2), on the other hand, involves a larger scaling of immediate technologies as well as the adoption of innovations such as the use of additives, representing a model that would be more likely to be adopted by a risk-tolerant farmer. The Bovaer (3NOP) additive has been trialled at FZC for methane reduction, and based on these results and the results of previous studies, a 28% reduction was estimated during housing with a 10% reduction throughout the grazing period [40–42]. The environmental impact is limited to GHG emissions (carbon footprint) only. The description of the strategies employed in the baseline and the two scenarios (S1 and S2) is summarised in Table 3.

Table 3. Scenarios under consideration.

Strategy	Baseline	S1	S2
Reduce Chemical N	No change (220 kgN/ha)	To 185 kg N/ha (16%) -Include white clover on 25% of pasture area -Include red clover on 10% of silage area -Include MSS on 10% of pasture area	To 150 kg N/ha (45%) -Include white clover on 50% of pasture area -Include red clover on 25% of silage area -Include MSS on 20% of pasture area
Grazing management	235 Days grazing Season	Extend grazing season by 7 days	Extend grazing season by 14 days
Protected urea	0% of chemical N	50% of chemical N	100% of chemical N
Slurry spreading season	50% Summer, 50% Spring	50% in Summer, 50% in Spring	80% in Spring, 20% in Summer
Slurry spreading method	Splash plate	LESS	LESS
Chemically amend slurry	0% Slurry	0% of slurry	100% of slurry
Native feeds	0% of feed	50% of the diet is native	100% of the diet is native
Reduce feed concentrate	No change	By 5%	By 10%
Anti-methanogenic feeds (Bovaer)	No change	No change	Throughout the year—housing + grazing (28% reduction during housing and 10% when grazing).
Reduce replacement rate	No change (22%)	To 20%	To 18%
Use renewable sources to reduce energy inputs	No change	By 25%	By 50%
Increase production of milk solids (EBI—management practices)	No change	No changes	By 5%

2.4. Economic Impact Analysis

The scenarios were modelled to determine the changes in net profit under different levels of mitigation. Firstly, a whole farm budget was prepared for a typical average dairy farm using farm-level data and the 2022 National Farm Survey (NFS) results to create a baseline [12]. The basic components of the dairy budget were adopted from the Teagasc Profit Monitor tool, which is a digital tool used by farmers to assess their profit/loss over a period of time [43]. Components of the data include the revenue, variable costs, fixed costs and net profit as presented in Equation (1).

$$\text{Profit or loss} = \text{Total Revenue} - \text{Total Cost} \quad (1)$$

where profit or loss is the amount remaining after removing total costs from the gross total revenue [44].

Farm gross revenue was calculated by combining milk sales receipts, cow sales, and the average value of calves sold. Market values for revenue items were adopted from [45] and [46] as follows: farm gate milk price of EUR 0.41/L of milk, EUR 1300/culled cow and EUR 169/calf. Costs were split into variable costs and fixed costs. Variable costs are those costs that vary per scale of production [47,48]. The major variable costs were fertiliser, concentrates, reseeding, replacement rearing, and contractor costs. Fixed costs are costs which do not vary with the level of production ha [43]. Fixed costs include machinery running and lease costs, hired labour, repairs and maintenance and overheads. Expenses such as depreciation and loan repayment were not included in order to simplify the model.

Partial Budget Analysis

A partial budget was then used to check the overall changes in net profit under the two scenarios. The changes resulting from adopting and implementing the mitigation strategies only affect a part of the business and mostly the direct costs, as such, a partial budget was applicable for the analysis of the impact of such changes [49]. Using a partial budget, one can evaluate whether a change in management will increase or decrease profit [50]. The method does not determine profit; rather, it checks the changes in net profit which is recorded as net benefit:

$$\text{Net benefit} = \text{Total benefit change} - \text{Total cost change} \tag{2}$$

$$\text{Total benefit Change} = \text{Extra revenue} + \text{Cost saved} \tag{3}$$

$$\text{Total cost change} = \text{Total cost increased} + \text{Revenue forgone} \tag{4}$$

where total benefit change is the summation of extra revenue increased plus cost saved, and total cost change is the total cost increased plus the revenue forgone [49].

The partial budget economic analysis involves understanding the changes in costs and/or revenues associated with various climate change mitigation strategies demonstrated through FZC. The net benefit, expressed in EUR/Farm/year, can also be referred to as net annual profit, which is the total of the marginal benefits accruing from the net savings on each strategy. A positive margin implies an increase in net profits, whereas a negative figure implies that the introduction of the mitigation strategies reduces net farm profit.

2.5. Environmental Impact Analysis

To quantify the environmental footprint of a conventional farm, a LCA model was initially developed for the FZC farm using 2018 and 2022 data, and subsequently, data were adapted for the average farm. The LCA methodology, guided by the International Standardization Organization's (ISO) framework of goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040:2006) was used to calculate the global warming potential [51]. The cradle-to-farm gate system boundary was used, and the functional unit was the kg carbon dioxide equivalent per kilogram of fat- and protein-corrected milk (kg CO_2-eq/kg FPCM). The methodology and functional unit used measured the GHG intensity rather than absolute emissions. In essence, a reduction in kg CO_2-eq/kg FPCM means the kg of milk on the dairy farm was produced with a lower carbon footprint [5]. The life cycle inventory analysis was carried out using the LCA model developed at FZC (yet to be published) and average figures from the 2022 National Farm Survey data (highlighted in Table 1) were used to simulate the baseline farm. The model was populated using data on animal performance, fertiliser application, manure management, forage production and energy consumption. The calculations are based on the Intergovernmental Panel on Climate Change (IPCC) tier 2 and tier 3 by using country-specific emissions factors from different sources including Ireland's National Inventory Report 2022 [52], Ireland's Informative Inventory Report 2018 [53], the European

Environment Agency's 2019 Air Pollutants Report [54], and the IPCC's 2019 updates to its 2006 publication [55,56].

3. Results

3.1. Baseline

Using the variables described in Table 1 the baseline scenario was first modelled to find the net profit and GHG emissions of the farm before any climate change mitigation measure was applied. Table 4 provides a major summary of the costs, revenue and profit from the case study farm. Total revenue from the sale of milk, culled cows and calves was EUR 255,678. Total variable costs were calculated as EUR 116,087 with the high costs of fertiliser and concentrate the major factor in the high variable costs. The net profit was estimated to be EUR 84,265 for the baseline. Similarly, the net profit for S1 and S2 was estimated as EUR 90,900 and EUR 102,311, respectively.

Table 4. Dairy enterprise budget.

	Baseline	**S1**	**S2**
Annual concentrates fed (kg/cow)	1100 kg	1045 kg	990 kg
Milk yield (L/cow)	530,100 L	530,100 L	556,605 L
Milk sales (EUR)	12,337 EUR	12,506 EUR	12,844 EUR
Meat sales (EUR)	38,337 EUR	38,506 EUR	38,844 EUR
Total Sales(EUR)	255,678 EUR	255,847 EUR	267,052 EUR
Variable costs			
Concentrates (EUR)	43,682 EUR	41,491 EUR	39,145 EUR
Fertiliser (EUR)	18,533 EUR	14,574 EUR	10,998 EUR
Reseeding (EUR)	1633 EUR	2163 EUR	2799 EUR
Additives (EUR)	-	-	8079 EUR
Replacements rearing (EUR)	21,769 EUR	20,269 EUR	17,269 EUR
Contractor costs (EUR)	15,874 EUR	16,529 EUR	16,529 EUR
Veterinary and breeding (EUR)	14,596 EUR	14,596 EUR	14,596 EUR
Total variable costs (EUR)	116,087 EUR	109,622 EUR	109,416 EUR
Gross margin (EUR)	139,591 EUR	146,225 EUR	157,636 EUR
Fixed costs			
Total fixed costs (EUR)	55,325 EUR	55,325 EUR	55,325 EUR
Net Income(cash) (EUR)	84,266 EUR	90,900 EUR	102,311 EUR
Net Savings(cash) (EUR)	-	6634 EUR	18,045 EUR

For the environmental metrics, only the GHG emissions were considered and the absolute farm emissions for the baseline was 534 tonnes CO_2. The emission intensity expressed per unit of product using LCA was modelled to be 0.96 $kgCO_2eq/kg$ FPCM, before any form of intervention as shown in Figure 1. The main emission sources were animal digestion (0.505 kg), manure management (0.130 kg) and fertiliser use (0.155 kg). Animal digestion constitutes 52% of the farm emissions.

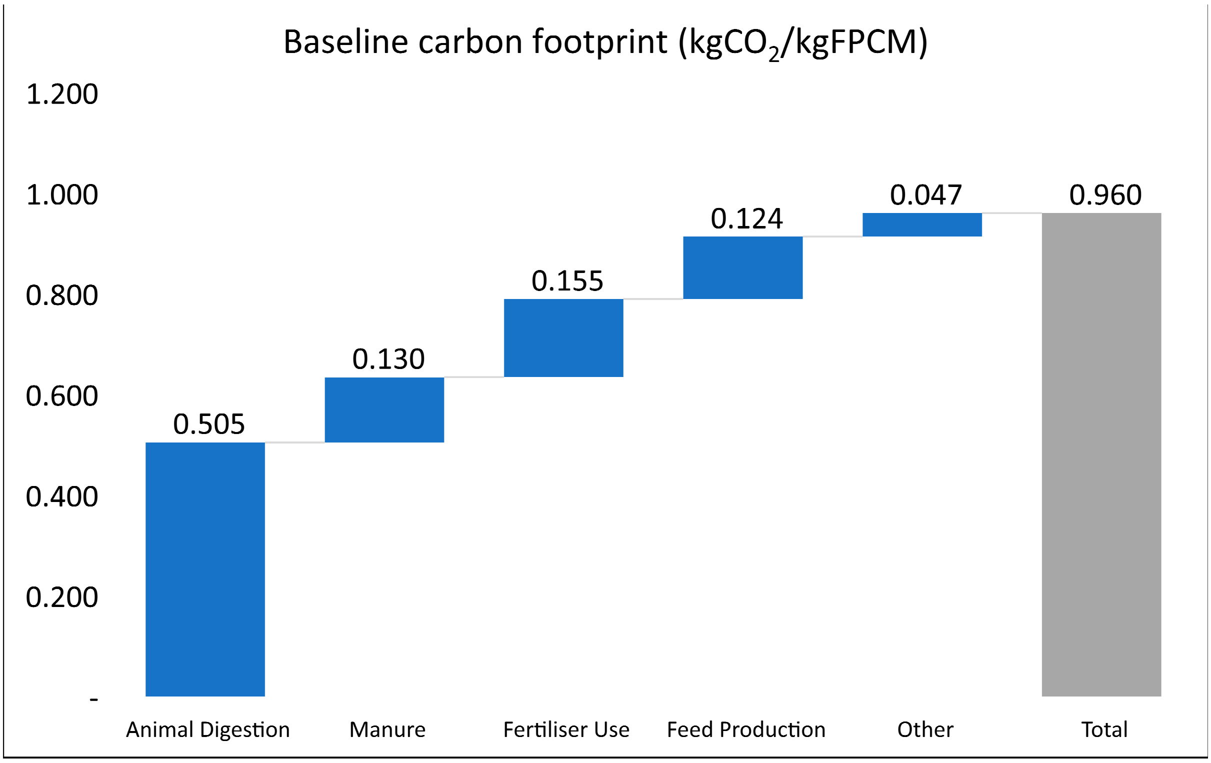

Figure 1. Baseline GHG emissions.

3.2. Changes in Net Profit under Different Scenarios

The partial budget results are shown in Table 5. Savings were realised from fertiliser savings, savings in concentrate and the reduced cost of rearing heifers for replacement. Incremental costs were also realised for reseeding and contractors' costs for both scenarios. The cost of slurry and anti-methanogenic additives were the major costs of the mitigation strategies employed. Extra revenue was realised from extra milk sales, replacement sales and fertiliser savings.

Table 5. Net benefit from different scenarios.

Cost/Benefit (EUR)	S1	S2
Cost saved		
Fertiliser savings (EUR)	3959 EUR	7535 EUR
Concentrate (EUR)	2191 EUR	4537 EUR
Replacement rate (EUR)	1500 EUR	4500 EUR
Extra revenue(EUR)		
Extra sales (EUR)	169 EUR	11,374 EUR
Extra costs incurred		
Reseeding (EUR)	−530 EUR	−1166 EUR
Additives (EUR)	0 EUR	−8079 EUR
Contractor costs (EUR)	−655 EUR	−655 EUR
Net Benefit	6634 EUR	18,045 EUR

All costs and benefits are expressed in euros (EUR). The negative sign represents a loss or cost.

3.2.1. Costs Saved

Major costs forgone were the reduced fertiliser, concentrate and replacement heifer rearing costs. Fertiliser reduction was due to the use of clover and MSS swards to reduce the need for chemical N fertiliser. The switching from calcium ammonium nitrate (CAN) to protected urea also resulted in large savings because 1 kg of protected urea would cost EUR 0.18 less than CAN. Generally, large savings of EUR 3959 and EUR 7535 were realised in S1 and S2, respectively. This could be attributed to higher fertiliser prices experienced in 2022 and 2023. The reduction in concentrate resulted in net savings of EUR 3649 and EUR 4536, respectively, in S1 and S2. Extra savings were also realised from the reduced cost of rearing replacement heifers.

3.2.2. Extra Revenue

For Scenario 2, extra sales were recognized from increased productivity, as annual milk yield per cow increased from 530,100 L to 556,605 L due to a higher EBI and improved management. This results in an increase of EUR 11,374 in revenue under S2.

3.2.3. Extra Costs

Under Scenario 2, feed and slurry additives were the major costs amounting to EUR 8079.

The reseeding costs were the common costs in both S1 and S2, as clover and MSS would need more frequent reseeding than the grass swards. However, these reseeding costs were offset by the large fertiliser savings.

3.2.4. Net Profit/Loss

The economic modelling showed an increase in net farm profit in both Scenarios 1 and 2. Under S1, where the farmer applied minimum measures for climate change mitigation, a net farm profit increase of EUR 6634 was achieved, and a larger profit (EUR 18,045) was realised for S2. Though high costs were realised for the use of additives, these costs were neutralised by savings from reduced fertiliser use and increased productivity. A positive figure shows that the overall impact of the intervention provides a profit rather than a loss. Farmers may be more willing to adopt the interventions modelled in both scenarios as they have a positive net economic benefit.

3.3. Environmental Impact

Following LCA modelling of climate change mitigation strategies for both scenarios, changes were noted across the main categories of emission sources as shown in Figure 2. The GHG emissions were reduced to 0.847 kg of CO_2-eq/kgFPCM and 0.614 kg of CO_2-eq/kgFPCM, in S1 and S2, respectively.

3.3.1. Animal Digestion

Methane emissions from enteric fermentation were the dominant source of GHG emissions, contributing 56% (0.458 kg of CO_2-eq) of the total GHG emissions under S1 and 62% (0.409 kg of CO_2-eq) per kilogram of FPCM under S2. A 28% methane emission reduction during the housing period and a 10% reduction during the grazing season were assumed for S2, where anti-methane additives were used. This resulted in a 12% emission reduction from animal digestion in S2.

3.3.2. Manure Management

As compared to the baseline, manure accounted for a greater percentage of total emissions than fertiliser, after climate change mitigation strategies were applied. By extending the grazing season and applying manure management of chemically amending slurry, applying slurry during favourable weather conditions and using LESS for spreading slurry, the emissions from manure decreased from 0.13 to 0.122 and 0.073 kg CO_2-eq/kgFPCM, in S1 and S2, respectively.

3.3.3. Fertiliser Use

Nitrogen fertiliser use is responsible for nitrous oxide emissions during the fertiliser application and production processes. The use of protected urea and a reduction in the quantity of nitrogen fertiliser applied saw the fertiliser emissions drop by 3.3% and 7.1% for S1 and S2, respectively.

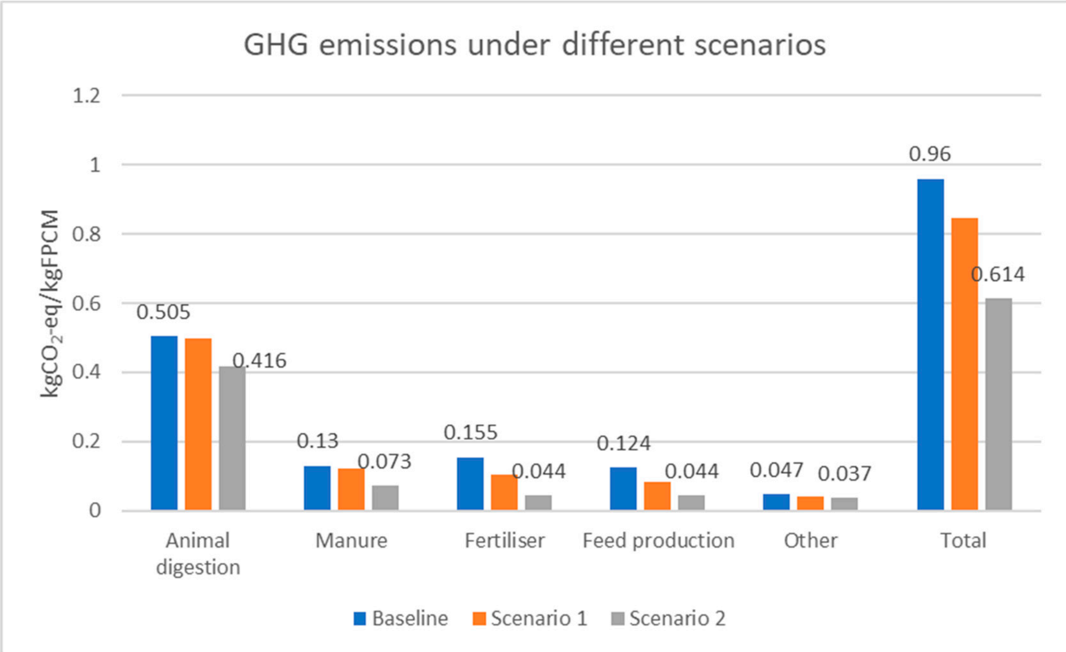

Figure 2. Changes in GHG emissions under different scenarios.

3.3.4. Feed Production

Ireland mainly depends on feed imports such as soya from Brazil and grain from America for concentrate ingredients, which have higher GHG emissions from land use changes and transport than local ingredients. A reduction in feed concentrates and sourcing of EU-produced feed ingredients had a significant reduction in emissions from feed production, with a decrease from the baseline of 0.124 to 0.083 and 0.44 kg CO_2-eq/kgFPCM, in S1 and S2, respectively.

3.3.5. Other

The category "other" represented all emissions from the farm which may not fall into the broader categories, for example, farm energy use. Energy demand reductions for farm applications, such as manure spreading and fertiliser applications, would result in lower on-farm CO_2 emissions.

3.3.6. Net Environmental Impact

The overall results show a net reduction in GHG emissions of 12% from 0.96 kg of CO_2-eq/kgFPCM to 0.847 under S1, and in S2 where the farm-level strategies are employed at a larger scale there was a 36% reduction in emissions the final footprint was 0.614 kg CO_2-eq/kgFPCM.

4. Discussion

Irish farmers need to move towards climate neutrality by adopting robust but practical technologies which ensure both the environmental and economic sustainability of dairy farms. The national emission reduction target of 25% is based on absolute farm emissions using the IPCC methodology [5]. In the FZC case study, the LCA methodology, which considers emissions from upstream processes such as fertiliser and feed production, was used. The results show the reduction in emissions per kilogram of milk, which is an important measure at the farm level for farmers to be able to understand how their environmental decisions affect the farm profit.

4.1. Economic Impact

The baseline represents an average commercial dairy farm which is economically sustainable, as evidenced by a net profit of EUR 84,265. The higher revenues, as compared to the previous seasons, can be attributed to higher farmgate milk prices [12]. According to the NFS results, fertiliser and concentrate feeds are the major variable costs, with fertiliser contributing almost 20% to the total variable costs [12]. The results are in line with [11], which indicates that more grass in the diet increases the profitability of the farming system, and increasing more concentrate feeds is not always the most economically rational choice. The reduction in the quantity of concentrate feeds is not expected to reduce the productivity of the farm, as the assumption is that any dry matter shortfall is compensated for by grassland management practices such as extending the grazing season [44]. Farmers are expected to reduce their concentrate feed not only due to the environmental benefits but also the realisation of cost reduction opportunities. This is in line with evidence from an online survey of 396 Irish farmers, which showed 73% support for the paradigm of maximizing milk from forage and minimizing concentrate use [57] for both environmental and economic gains. Major incremental gains were also realised from increasing the EBI of the herd. The EBI is an efficiency tool which aims to improve the genetic merit of animals for increased profitability. In line with [24], the increase in dairy productivity would result in reduced emission intensity but absolute farm emissions may not drop.

Though large methane emission reductions were realised from the anti-methane additives in S2, it was determined from this analysis that the additives were the major incremental costs in the dairy system under S2. The costs of anti-methane additives represent a major challenge to the adoption of the strategy, as previous research has shown that costly mitigation strategies are a huge disincentive [23].

Other Opportunities for Revenue Generation

The partial budget results in Section 3 indicate the likely increase in net profit by adopting the current farm-level FZC mitigation opportunities; however, by following specific MRV standards, the products can be certified as "carbon reduced" or "carbon free". Where an MRV procedure can be established and the emission abatement can be attributed to specific strategies, the farmers can potentially obtain money from carbon credits or market premiums. In the EU, a tonne of CO_2 is expected to cost EUR 140 by 2030 [58]; hence, under the S2 scenario, farmers have the potential to earn up to EUR 20,580 from abating 147 tonnes of CO_2. A recent Irish consumer survey of 1500 adults showed that 72% of respondents were willing to pay more for dairy products, provided they see the evidence that the increase is going to embed the latest environmental initiatives in production [59]. This view is reiterated by [60]'s findings on consumers' perceptions of carbon footprint labels for dairy products in Italy, which shows that consumers would be willing to pay extra when they are fully aware of the products and claims made about the carbon footprint.

4.2. Environmental Impact

In contrast to indoor systems where manure is the largest contributor to GHG emissions, in grass-based systems, total emissions consist mainly of methane emissions from enteric fermentation [33]. Scenario 2 resonates with target resource use efficiency systems simulated by [61,62] whose results concur with the current study. Both studies found that methane emissions in target farms would contribute a larger percentage to overall GHG than the baseline current farm with lower efficiency. The results highlight the need to reduce methane emissions in grass-based systems. The additive Bovaer (3NOP) has shown consistency in methane reduction with an average of 30% reduction when administered in feed for dairy cows [42,63,64]. However, there are practical issues around administration of the additives in grass-based systems. The adoption rate of additives in general is expected to be low, as there are issues regarding social acceptance and the cost of the additives [65]. Previous studies have suggested the use of slow-release bolus to incorporate the additives in pasture-based systems where 95% of the animals' diet is from grazed forage [41,63].

The reduction in fertiliser emissions in both S1 and S2 is a result of nitrous oxide reduction. Nitrous oxide emissions account for 25% of the agricultural sector's emissions in Ireland [35]. In line with [22,37], the FZC case study highlights the importance of incorporating clover and minimising chemical fertiliser for grassland productivity. This also concurs with [33], who showed that nitrogen surplus from chemical nitrogen per hectare was positively correlated to the GHG emission intensity of milk. According to [66], animal excreta and urine are the biggest sources of N_2O per year in grasslands, followed by manure applications. Manure acts as an emission source for both methane and nitrous oxide, and the quantity emitted is linked to environmental conditions, type of management and composition of the manure [67]. By extending the grazing season and applying manure management strategies, fewer emissions are released from the storage and application of manure. The overall reduction in emissions from manure management in both S1 and S2 results shows that though extending the grazing season results in more N emissions from excreta deposited on grassland, the reduction in emissions from stored manure will be higher than the marginal increase from manure deposits [33]. In contrast to confinement systems, in grass-based systems, the total GHG emissions associated with feed production are predominantly from grass [61].

The results show that to achieve climate neutrality in dairy systems by 2050, a holistic approach which combines different mitigation strategies at significant but reasonable levels (e.g., S2) of application is required. Farmers are still able to achieve a notable emission reduction of 12% under S1 without incorporating new technologies such as anti-methane additives. The results concur with studies by [62], in Ireland and [19] in New Zealand, which showed that combining climate mitigation strategies that increase production efficiencies, resulted in substantial emission reduction for grass-based systems. The business case underlines the significance of using multiple measures in reducing climate change as there are no quick fixes to achieving net zero emissions [68]. It is important to highlight that efficient use of resources can offer additional benefits, other than reducing costs and carbon dioxide emissions. A study by [62] has already shown that moving to a target-efficient system would reduce freshwater eutrophication, acidification, and non-renewable energy depletion in Irish dairy. As more consumers become more responsible for their purchasing behaviour by purchasing environmentally friendly products [59,60], and reducing food waste and losses, this case study shows that there are potential positive ripple effects of holistic sustainable production [69]. Such solutions are important to achieve all three dimensions of environmental, economic and social sustainability [69].

Opportunities for Further Emission Reduction

While work remains to further reduce the emission footprint of the farm towards net zero, Shinagh Farm has several planned activities which can help to improve these scenarios. The project plans to implement a grass biorefinery and anaerobic digestion plant in 2024. The benefits of grass biorefinery to improve the use of grassland on dairy farms have previously been highlighted in Ireland through projects such as Biorefinery Glas and FZC. In this approach, fresh grass can be converted into multiple protein sources, including a press cake which is suitable for feeding ruminants and a leaf protein concentrate (LPC) which is suitable for feeding monogastric animals, such as pigs and poultry. Previous work from [70] has highlighted the potential for press cake to replace silage in dairy cow diets, achieving comparable milk yields, while offering a reduction in nutrient (nitrogen and phosphorus) excrement losses and delivering a higher nitrogen use efficiency. Work by [71,72] has shown that the extracted protein LPC can serve as a suitable replacement for imported soya bean meal in the diets of pigs. By creating "off-farm" products, the biorefinery approach can help the farm to achieve further environmental benefits by enabling a redistribution of the environmental impacts associated with grassland production. The inclusion of anaerobic digestion to produce biogas using farm residual streams is also expected to add further improvements to the current scenario. For example, ref. [73] has previously shown that small-scale anaerobic digestion of cattle slurry, co-digested with some grass from

Irish farms, can meet the farm's energy needs with surplus energy exported, representing between 73% and 79% of the total energy generated, with all scenarios investigated offering a net CO_2 emission reduction of approximately 173,237 kg CO_2-eq.yr^{-1}. In addition to the slurry, the residual streams or by-products such as grass whey and press cake from the grass biorefinery can also be utilised as a feedstock for biogas production, helping to further improve the sustainability and circularity of the farm model [72]. It is anticipated that a further 0.3 to 1.1 tonne CO_2/ha/yr reduction can be obtained from carbon sequestration from grassland management practices already employed at FZC as well as hedgerows.

5. Conclusions

To meet the GHG targets at the national and EU level without jeopardizing the economic viability of the sector, Irish agriculture needs to adopt practical climate mitigation strategies. Using partial budget analysis and LCA assessment to measure the change in farm profit and GHG emissions under different scenarios, the business case for an average Irish dairy farm was formed based on the FZC holistic approach. The FZC approach reiterates the importance of adopting win–win approaches also highlighted in the Teagasc MACC curve, such as the inclusion of clover, protected urea, slurry management and reducing feed concentrates immediately, as they result in lower operational costs. Evidence from S1 shows that by implementing these win–win solutions even at a small scale, a 16% reduction in GHG emissions can be achieved. Incremental costs are realised especially from methane additives, slurry amendments and the use of native feeds. Biogenic methane is the major GHG in grass-based systems; therefore, the use of methane additives for emission reduction should be considered a priority. As highlighted by the business case, anti-methane additives are costly. Subsidies or other financial policy incentives should be considered to foster the uptake of additives, especially during the period when the animals are housed as the additives are most effective.

While significant sustainability improvements can be achieved by implementing the current farm-level mitigation strategies at a higher scale (S2), these steps alone may not be sufficient to achieve climate neutrality, as shown by the reduction to 0.614 kg CO_2-eq/kg FPCM in S2. This means that there is a need for more research into additional climate mitigation measures in order to reach net zero emissions on the farm. Targeting net zero ensures that the environmental sustainability goals are achieved without compromising food security. More research should be invested towards the MRV of soil carbon sequestration potential of grasslands and hedgerows so that the contribution of soil organic carbon could be incorporated in future business cases. Other ways to further reduce the emissions include anaerobic biodigesters for renewable energy, and the implementation of biorefineries to improve the efficiency of grassland use. Consumers will also be crucial in driving the demand for climate-neutral agriculture; therefore, consumer-side policies should be aimed at increasing awareness of the climate change challenge. In addition, multi-actor partnerships would be crucial in the dissemination of information on climate change mitigation across the agricultural sector. Stakeholders like producer associations, dairy companies, cooperatives and advisory organisations should continue to advise farmers on low-carbon farming. The holistic approach to sustainable agricultural production can be instrumental in achieving other SDGs including food security, responsible production and consumption, and life in water and on the ground.

Author Contributions: Conceptualization, K.O., J.G., E.B. and F.M.; methodology, L.A.V., F.M., T.R. and G.H.; validation, K.O., J.G., F.M., E.B. and G.H.; formal analysis, T.R. and L.A.V.; investigation, data curation, G.H., T.R. and L.A.V.; writing—original draft preparation, T.R., L.A.V. and G.H.; writing—review and editing, K.O., J.G., F.M. and E.B.; visualization, L.A.V.; supervision, J.G.; project administration, G.H. and J.G.; funding acquisition, K.O., F.M., J.G. and E.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded through the Farm Zero C project by Science Foundation Ire-land's Zero Emissions Challenge, grant number 19/FIP/ZE/7558. The authors would like to acknowledge this funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is available upon a formal request.

Conflicts of Interest: Author E.B. is employed by Carbery group and the company was a partner in the FZC project.The authors declare no conflicts of interest.

References

1. Department of Agriculture Food and the Marine. Fact Sheet on Irish Agriculture. 2023. Available online: https://assets.gov.ie/246024/593efa4b-d404-41c2-8-08-eb459e1326cc.pdf (accessed on 11 September 2023).
2. Gaffey, J.; McMahon, H.; Marsh, E.; Vehmas, K.; Kymäläinen, T.; Vos, J. Understanding Consumer Perspectives of Bio-based Products—A Comparative Case Study from Ireland and the Netherlands. *Sustainability* **2021**, *13*, 6062. [CrossRef]
3. Department of the Environment, Climate and Communication. A Waste Action Plan for a Circular Economy. 2020. Available online: https://assets.gov.ie/8647/dcf554a4-0fb7-4d9c-9714-0b1fbe7dbc1a_3.pdf (accessed on 15 January 2024).
4. Ali, S.M.; Appolloni, A.; Cavallaro, F.; D'Adamo, I.; Di Vaio, A.; Ferella, F.; Gastaldi, M.; Ikram, M.; Kumar, N.M.; Martin, M.A.; et al. Development Goals towards Sustainability. *Sustainability* **2023**, *15*, 9943. [CrossRef]
5. Duffy, P.; Black, D.; Fahey, B.; Hyde, A.; Kehoe, E.; Kent, T.; MacFarlane, B.; Monoghan, J.; Murphy, J.; Ponzi, J.; et al. Ireland's National Inventory Report 2023. 2023. Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/NIR-2023-Final_v3.pdf (accessed on 21 October 2023).
6. Government of Ireland. CLIMATE ACTION PLAN 2021 Securing Our Future. 2021. Available online: https://assets.gov.ie/203546/a183a324-40ed-49c9-b630-bab0fbdd2ce2.pdf (accessed on 4 April 2023).
7. Department of Environment, Climate and Communication. Ireland's Long-Term Strategy on Greenhouse Gas Emissions Reduction. 2023. Available online: https://assets.gov.ie/255743/35b2ae1b-effe-48af-aaf3-156dc5b01ee6.pdf (accessed on 12 October 2023).
8. Buckley, C.; Donnellan, T.; Moran, B.; Lennon, J.; Brennan, J.; Colgan, J.; Curley, A.; Deane, L.; Doyle, T.; Harnett, P.; et al. *Teagasc National Farm Survey 2021 Sustainability Report*; Teagasc, Athenry, Co.: Galway, Ireland, 2022.
9. Central Statitics Office. Environmental Indicators Ireland: Irish Land Use Categories 1990–2020. Available online: https://www.cso.ie/en/releasesandpublications/ep/p-eii/environmentalindicatorsireland2022/landuse/ (accessed on 2 July 2023).
10. O'Mara, F.; Richards, K.G.; Shalloo, L.; Donnellan, T.; Finn, J.A.; Lanigan, G. Sustainability of Ruminant Livestock Production in Ireland. *Anim. Front.* **2021**, *11*, 32–43. [CrossRef] [PubMed]
11. Ramsbottom, G.; Horan, B.; Pierce, K.M.; Berry, D.P.; Roche, J.R. A Case Study of Longitudinal Trends in Biophysical and Financial Performance of Spring-Calving Pasture-Based Dairy Farms. *Int. J. Agric. Manag.* **2020**, *9*, 33–44.
12. Dillon, E.; Donnellan, T.; Moran, B.; Lennon, J. Teagasc National Farm Survey 2022. 2023. Available online: https://www.teagasc.ie/publications/2023/teagasc-national-farm-survey-2022.php (accessed on 3 October 2023).
13. Department of Agriculture, Food and the Marine. Fact Sheet on Irish Agriculture Key Indicators for Agri-Food Sectors. 2020. Available online: https://assets.gov.ie/88632/eff46189-8124-4072-9526-c49f995833b9.pdf (accessed on 5 November 2023).
14. Chen, R.; Zhang, R.; Han, H. Climate Neutral in Agricultural Production System: A Regional Case from China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 33682–33697. [CrossRef] [PubMed]
15. Searchinger, T.; Zionts, J.; Wirsenius, S.; Peng, L.; Beringer, T.; Dumas, P.; Rahbek, C.; Kvist Johannsen, V.; Jacobesen, B.; Bredahl, J.; et al. A Pathway to Carbon Neutral Agriculture in Denmark. 2021. Available online: https://d30mzt1bxg5llt.cloudfront.net/public/uploads/PDFs/carbon-neutral-agriculture-denmark.pdf (accessed on 3 August 2023).
16. Kingwell, R. Making agriculture Carbon Neutral amid a Changing Climate: The Case of South-Western Australia. *Land* **2021**, *10*, 1259. [CrossRef]
17. Sanderman, J. Can Management Induced Changes in the Carbonate System Drive Soil Carbon Sequestration? A Review with Particular Focus on Australia. *Agric. Ecosyst. Environ.* **2012**, *155*, 70–77. [CrossRef]
18. Kragt, M.E.; Pannell, D.J.; Robertson, M.J.; Thamo, T. Assessing Costs of Soil Carbon Sequestration by Crop-Livestock Farmers in Western Australia. *Agric. Syst.* **2012**, *112*, 27–37. [CrossRef]
19. Yang, W.; Rennie, G.; Ledgard, S.; Mercer, G.; Lucci, G. Impact of Delivering 'Green' Dairy Products on Farm in New Zealand. *Agric. Syst.* **2020**, *178*, 102747. [CrossRef]
20. Forrestal, P.; Somers, C.; Plunkett, M.; Wall, D.; O'dwyer, T. Protected Urea: What Is It, Does It Work, and Is It Cost Effective? 2019. Available online: https://www.teagasc.ie/media/website/environment/climate-change/Andy-Boland--Patrick-Forrestal-Protected-Urea-April-2019-resized.pdf (accessed on 2 April 2023).
21. Mccarthy, K.; Mcaloon, C.; Lynch, B.; Pierce, K.; Mulligan, F.; Totty, V.; Greenwood, S.; Bryant, R.; Edwards, G. The effect of a zero-grazed perennial ryegrass, perennial rye-grass and white clover, or multispecies sward on the dry matter intake and milk production of dairy cows. *Anim. Sci. Proc.* **2021**, *12*, 96. [CrossRef]

22. Egan, M.; Galvin, N.; Hennessy, D. Incorporating White Clover (*Trifolium Repens* L.) into Perennial Ryegrass (*Lolium Perenne* L.) Swards Receiving Varying Levels of Nitrogen Fertilizer: Effects on Milk and Herbage Production. *J. Dairy Sci.* **2018**, *101*, 3412–3427. [CrossRef]
23. Farstad, M.; Melås, A.M.; Klerkx, L. Climate Considerations aside: What Really Matters for Farmers in Their Implementation of Climate Mitigation Measures. *J. Rural. Stud.* **2022**, *96*, 259–269. [CrossRef]
24. Läpple, D. Information about Climate Change Mitigation: What Do Farmers Think? *EuroChoices* **2023**, *22*, 74–80. [CrossRef]
25. Geoghegan, C.; O'donoghue, C.; Loughrey, J. The Local Economic Impact of Climate Change Mitigation in Agriculture. *Bio-Based Appl. Econ.* **2022**, *11*, 323–337. [CrossRef]
26. Lanigan, G.J.; Hanrahan, K.; Richards, K.G.; Lanigan, G.; Black, K.; Donnellan, T.; Crosson, P.; Beausang, C.; Buckley, C.; Lahart, B.; et al. *MACC 2023: An Updated Analysis of the Greenhouse Gas Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030 Prepared by Teagasc Climate Centre*; Teagasc: Oak Park, Carlow, Ireland, 2023.
27. Lalor, S.T.J.; Schröder, J.J.; Lantinga, E.A.; Oenema, O.; Kirwan, L.; Schulte, R.P.O. Nitrogen Fertilizer Replacement Value of Cattle Slurry in Grassland as Affected by Method and Timing of Application. *J. Environ. Qual.* **2011**, *40*, 362–373. [CrossRef] [PubMed]
28. Lahart, B.; Shalloo, L.; Herron, J.; O'Brien, D.; Fitzgerald, R.; Boland, T.M.; Buckley, F. Greenhouse Gas Emissions and Nitrogen Efficiency of Dairy Cows of Divergent Economic Breeding Index under Seasonal Pasture-Based Management. *J. Dairy Sci.* **2021**, *104*, 8039–8049. [CrossRef]
29. Biorefinery Glas. Grass Biorefinery. 2020. Available online: https://biorefineryglas.eu/wp-content/uploads/2020/02/factsheet-1.pdf (accessed on 27 November 2023).
30. Visser, S.; Lhermite, E.; Keesstra, S. The Innovation Potential for the Irish Agri-Food Sector 2. Carbon Farming. 2023. Available online: https://www.climate-kic.org/wp-content/uploads/2023/03/EIT-Climate-KIC_Report_Dealing-with-climate-change-and-sustainability-targets.pdf (accessed on 30 June 2023).
31. Cahill, L.; Patton, D.; Reilly, B.; Pierce, K.M.; Horan, B. Grazing Season Length and Stocking Rate Affect Milk Production and Supplementary Feed Requirements of Spring-Calving Dairy Cows on Marginal Soils. *J. Dairy Sci.* **2023**, *106*, 1051–1064. [CrossRef] [PubMed]
32. Johnston, D.J.; Laidlaw, A.S.; Theodoridou, K.; Ferris, C.P. Performance and Nutrient Utilisation of Dairy Cows Offered Silages Produced from Three Successive Harvests of Either a Red Clover–Perennial Ryegrass Sward or a Perennial Ryegrass Sward. *Ir. J. Agric. Food Res.* **2020**, *59*, 42–55. [CrossRef]
33. O'Brien, D.; Hennessy, T.; Moran, B.; Shalloo, L. Relating the Carbon Footprint of Milk from Irish Dairy Farms to Economic Performance. *J. Dairy Sci.* **2015**, *98*, 7394–7407. [CrossRef]
34. Forrestal, P. Manure and It's Management-Focus on Cattle Slurry. In Proceedings of the Soil Fertility Conference: Optimising Soil and Fertiliser for Sustainable Grassland Management, Kilkeny, Ireland, 17 October 2018.
35. Lanigan, G.J.; Donnellan, T.; Lanigan, G.; Hanrahan, K.; Paul, C.; Shalloo, L.; Krol, D.; Forrestal, P.; Farrelly, N.; O'brien, D.; et al. *An Analysis of Abatement Potential of Greenhouse Gas Emissions in Irish Agriculture 2021–2030 Prepared by the Teagasc Greenhouse Gas Working Group Authors*; Teagasc: Oak Park, Carlow, Ireland, 2019.
36. Agritech.ie. Prepare for Calving 2023. Available online: https://agritech.ie/preparing-for-calving-2023/ (accessed on 3 August 2023).
37. Ruelle, E.; Delaby, L.; Shalloo, L.; O'Donovan, M.; Hennessy, D.; Egan, M.; Horan, B.; Dillon, P. Modelling the Effects of Stocking Rate, Soil Type, Agroclimate Location and Nitrogen Input on the Grass DM Yield and Forage Self-Sufficiency of Irish Grass-Based Dairy Production Systems. *J. Agric. Sci.* **2022**, *160*, 235–249. [CrossRef]
38. McClearn, B.; Shalloo, L.; Gilliland, T.J.; Coughlan, F.; McCarthy, B. An Economic Comparison of Pasture-Based Production Systems Differing in Sward Type and Cow Genotype. *J. Dairy Sci.* **2020**, *103*, 4455–4465. [CrossRef]
39. Yan, M.J.; Humphreys, J.; Holden, N.M. The Carbon Footprint of Pasture-Based Milk Production: Can White Clover Make a Difference? *J. Dairy Sci.* **2013**, *96*, 857–865. [CrossRef]
40. Martinez-Fernandez, G.; Duval, S.; Kindermann, M.; Schirra, H.J.; Denman, S.E.; McSweeney, C.S. 3-NOP vs. Halogenated Compound: Methane Production, Ruminal Fermentation and Microbial Community Response in Forage Fed Cattle. *Front. Microbiol.* **2018**, *9*, 1582. [CrossRef]
41. Cummins, S.; Lanigan, G.J.; Richards, K.G.; Boland, T.M.; Kirwan, S.F.; Smith, P.E.; Waters, S.M. Solutions to Enteric Methane Abatement in Ireland. *IJAFR* **2022**, *61*, 353–371. [CrossRef]
42. Melgar, A.; Lage, C.F.A.; Nedelkov, K.; Räisänen, S.E.; Stefenoni, H.; Fetter, M.E.; Chen, X.; Oh, J.; Duval, S.; Kindermann, M.; et al. Enteric Methane Emission, Milk Production, and Composition of Dairy Cows Fed 3-Nitrooxypropanol. *J. Dairy Sci.* **2021**, *104*, 357–366. [CrossRef]
43. Hanrahan, L.; McHugh, N.; Hennessy, T.; Moran, B.; Kearney, R.; Wallace, M.; Shalloo, L. Factors Associated with Profitability in Pasture-Based Systems of Milk Production. *J. Dairy Sci.* **2018**, *101*, 5474–5485. [CrossRef] [PubMed]
44. Ramsbottom, G.; Horan, B.; Berry, D.P.; Roche, J.R. Factors Associated with the Financial Performance of Spring-Calving, Pasture-Based Dairy Farms. *J. Dairy Sci.* **2015**, *98*, 3526–3540. [CrossRef] [PubMed]
45. Board Bia. Export Performance and Prospects Report 2022–2023. 2023. Available online: https://www.bordbia.ie/globalassets/bordbia.ie/industry/2022---2023-export-performance--prospects-final.pdf (accessed on 21 June 2023).
46. National Dairy Council. Dairy in a Healthy and Sustainable Irish and European Food System. *Dairy Sustainability Newsletter. Issue No 003*. 2022. Available online: https://ndc.ie/wp-content/uploads/2022/09/Dairy-Newsletter_Issue-2_Web.pdf (accessed on 17 August 2023).

47. Dillon, E.; Donnellan, T.; Moran, B.; Lennon, J. *Teagasc National Farm Survey 2020 Results Rural Economy Development Programme*; Teagasc: Athenry, Galway, Ireland, 2021.
48. Ramsbottom, G.; Cromie, A.R.; Horan, B.; Berry, D.P. Relationship between Dairy Cow Genetic Merit and Profit on Commercial Spring Calving Dairy Farms. *Animal* **2012**, *6*, 1031–1039. [CrossRef] [PubMed]
49. Soha, M.E.D. The Partial Budget Analysis for Sorghum Farm in Sinai Peninsula, Egypt. *Ann. Agric. Sci.* **2014**, *59*, 77–81. [CrossRef]
50. Jerlström, J.; Huang, W.; Ehlorsson, C.J.; Eriksson, I.; Reneby, A.; Comin, A. Stochastic Partial Budget Analysis of Strategies to Reduce the Prevalence of Lung Lesions in Finishing Pigs at Slaughter. *Front. Vet. Sci.* **2022**, *9*, 957975. [CrossRef] [PubMed]
51. *ISO 14040:2006*; Environmental Management-Life Cycle Assessment-Principles and Framework. Environmental Management System Requirements. International Organization for Standardization: Geneva, Switzerland, 2004.
52. Duffy, P.; Black, K.; Fahey, D.; Hyde, B.; Kehoe, A.; Monoghan, S.; Murphy, J.; Ryan, A.M.; Ponzi, J. *Ireland's National Inventory Report 2022*; The Environemntal Protection Agency; Johnstown Castle, Co.: Wexford. Ireland, 2022; Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland-NIR-2022_Merge_v2..pdf (accessed on 12 April 2023).
53. Duffy, P.; Hyde, B.; Ryan, A.M.; Alam, M.S. *Ireland's Informative Inventrory Report 2018*; The Environemntal Protection Agency; Johnstown Castle, Co.: Wexford, Ireland, 2018; Available online: https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland-IIR-2018_Final.pdf (accessed on 12 April 2023).
54. European Environment Agency. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019: Technical Guidance to Prepare National Emission Inventories*; Publications Office of the European Union: Copenhagen, Denmark, 2019; Available online: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/download (accessed on 6 April 2023).
55. Intergovernmental Panel on Climate Change. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *Chapter 11 N2O Emissions from Managed Soils and CO2 Emissions from Lime and Urea Application.* 2019. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf (accessed on 13 April 2023).
56. Intergovernmental Panel on Climate Change. Refinement to the 2006 IPCC Guidelines for National Inventories, Chapter 10 Emissions from Livestock and Manure Management 2019. 2019. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch10_Livestock.pdf (accessed on 13 April 2023).
57. Shortall, O.K.; Lorenzo-Arribas, A. Dairy Farmer Practices and Attitud es Relating to Grass-Based, High-Feed-Input, and Indoor Production Systems in Ireland. *J. Dairy Sci.* **2022**, *105*, 375–388. [CrossRef] [PubMed]
58. KPMG. Agri-Food 2030: How the Sector Can Turn Disruption into Opportunity Your Partner for What's Next. 2022. Available online: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/ (accessed on 4 September 2023).
59. Board Bia. Buyer Guide: Grass Fed Dairy from Ireland Buyer Guide: Grass Fed Dairy from Ireland 2. 2022. Available online: https://www.bordbia.ie/globalassets/bordbia2020/industry/sector-profile-blocks--images/dairy-brochures/buyer-guide---grass-fed-irish-dairy.pdf (accessed on 4 September 2023).
60. Canavari, M.; Coderoni, S. Consumer Stated Preferences for Dairy Products with Carbon Footprint Labels in Italy. *Agric. Food Econ.* **2020**, *8*, 1–16. [CrossRef]
61. O'Brien, D.; Shalloo, L.; Patton, J.; Buckley, F.; Grainger, C.; Wallace, M. A Life Cycle Assessment of Seasonal Grass-Based and Confinement Dairy Farms. *Agric. Syst.* **2012**, *107*, 33–46. [CrossRef]
62. Herron, J.; O'Brien, D.; Shalloo, L. Life Cycle Assessment of Pasture-Based Dairy Production Systems: Current and Future Performance. *J. Dairy Sci.* **2022**, *105*, 5849–5869. [CrossRef]
63. Van Wesemael, D.; Vandaele, L.; Ampe, B.; Cattrysse, H.; Duval, S.; Kindermann, M.; Fievez, V.; De Campeneere, S.; Peiren, N. Reducing Enteric Methane Emissions from Dairy Cattle: Two Ways to Supplement 3-Nitrooxypropanol. *J. Dairy Sci.* **2019**, *102*, 1780–1787. [CrossRef]
64. Yu, G.; Beauchemin, K.A.; Dong, R. A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. *Animals* **2021**, *11*, 3540. [CrossRef]
65. Beauchemin, K.A.; Ungerfeld, E.M.; Eckard, R.J.; Wang, M. Review: Fifty Years of Research on Rumen Methanogenesis: Lessons Learned and Future Challenges for Mitigation. In *Animal*; Cambridge University Press: Cambridge, UK, 2020; Volume 14, pp. S2–S16. [CrossRef]
66. Rivera, J.E.; Chará, J. CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. *Front. Sustain. Food Syst.* **2021**, *5*, 657936. [CrossRef]
67. Misselbrook, T.; Hunt, J.; Perazzolo, F.; Provolo, G. Greenhouse Gas and Ammonia Emissions from Slurry Storage: Impacts of Temperature and Potential Mitigation through Covering (Pig Slurry) or Acidification (Cattle Slurry). *J. Environ. Qual.* **2016**, *45*, 1520–1530. [CrossRef]
68. Emmet-Booth, J.P.; Dekker, S.; O'brien, P. Climate Change Mitigation and the Irish Agriculture and Land Use Sector. 2019. Available online: https://www.climatecouncil.ie/councilpublications/councilworkingpaperseries/Working%20Paper%20No.%205.pdf (accessed on 6 February 2023).
69. D'Adamo, I.; Desideri, S.; Gastaldi, M.; Tsagarakis, K.P. Sustainable Food Waste Management in Supermarkets. *Sustain. Prod. Consum.* **2023**, *43*, 204–216. [CrossRef]
70. Serra, E.; Lynch, M.B.; Gaffey, J.; M Sanders, J.P.; Koopmans, S.; Markiewicz-Keszycka, M.; McKay, Z.C.; Pierce, K.M. Biorefined Press Cake Silage as Feed Source for Dairy Cows: Effect on Milk Production and Composition, Rumen Fermentation, Nitrogen and Phosphorus Excretion and in Vitro Methane production. *Livest. Sci.* **2022**, *267*, 105135. [CrossRef]

71. Gaffey, J.; O'Donovan, C.; Murphy, D.; O'Connor, T.; Walsh, D.; Vergara, L.A.; Donkor, K.; Gottumukkala, L.; Koopmans, S.; Buckley, E.; et al. Synergetic Benefits for a Pig Farm and Local Bioeconomy Development from Extended Green Biorefinery Value Chains. *Sustainability* **2023**, *15*, 8692. [CrossRef]
72. Ravindran, R.; Koopmans, S.; Sanders, J.P.M.; McMahon, H.; Gaffey, J. Production of Green Biorefinery Protein Concentrate Derived from Perennial Ryegrass as an Alternative Feed for Pigs. *Clean Technol.* **2021**, *3*, 656–669. [CrossRef]
73. O'Connor, S.; Ehimen, E.; Pillai, S.C.; Lyons, G.; Bartlett, J. Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms. *Energies* **2020**, *13*, 637. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.