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Land Management Practices for FLAG Emissions Reduction and Removals Increase in Beef Production

A case study for IKEA

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Abstract

Beef production remains a primary contributor to greenhouse gas (GHG) emissions within the agricultural sector. This thesis evaluates the climate mitigation potential of various Land Management Practices (LMPs) by analyzing their capacity for both emission reduction and carbon sequestration. Through a systematic review of identifying the major emission contributors and relevant mitigation measures, Agroforestry, Rotational Grazing, and Cover Cropping were identified as high-impact strategies. To quantify these effects, a Life Cycle Assessment (LCA) was conducted on a mixed production case study (comprising both pasture and feedlot stages). Three scenarios were modeled: Baseline (Conventional), Rotational Grazing, and Cover Cropping. The results confirmed that these LMPs effectively targeted major emission contributors, aligning with established literature. Specifically, Rotational Grazing achieved a 13% reduction in total GHG emissions by optimizing machinery use and reducing fossil fuel inputs, while the Cover Cropping scenario yielded a 7% reduction. Regarding carbon removals, Soil Organic Carbon (SOC) was quantified using IPCC Tier 1 methodology, resulting in sequestration values of 0.087 kg C/ha/yr per kg LW for grass-based systems and 0.42 kg C/ha/yr per kg LW for Ryegrass + clover systems. However, the analysis identified significant methodological constraints in estimating carbon removals using static factors. The findings suggest that while LMPs offer substantial potential for Forest, Land, and Agriculture (FLAG) mitigation, their inherent biological complexity necessitates a more nuanced approach. Consequently, this study recommends for the adoption of a Hybrid LCA framework that integrates supply chain data with site-specific, process based modeling to accurately capture dynamic soil carbon fluctuations and long-term mitigation potential.

Keywords
FLAG, Beef Production, Agroforestry, Rotational Grazing, Cover Cropping, Life Cycle Assessment, Carbon removals.

Sammanfattning

Nötköttsproduktion är en av de största källorna till växthusgasutsläpp inom jordbruket. Denna avhandling undersöker hur olika metoder för markförvaltning (LMPs) kan minska klimatpåverkan, både genom lägre utsläpp och genom att binda kol i marken. Genom en genomgång av tidigare forskning identifierades skogsjordbruk (agroforestry), rotationsbetning och fånggrödor (cover crops) som de mest effektiva strategierna. För att mäta effekterna gjordes en livscykelanalys (LCA) på en gård med både betesdrift och uppfödning i stall (feedlot). Tre scenarier jämfördes: ett normalläge (Baseline), rotationsbetning och fånggrödor. Resultaten visade att dessa metoder minskade utsläppen från de största utsläppskällorna, vilket stämmer överens med tidigare forskning. Specifikt minskade rotationsbetning de totala utsläppen med 13 %, främst genom att minska användningen av maskiner och fossila bränslen. Fånggrödor gav en minskning på 7 %. När det gäller kolinlagring i marken användes en standardmetod (IPCC Tier 1). Resultaten visade att marken band 0,087 kg kol per kilo levandevikt för gräsmarker, och 0,42 kg för marker med engelskt rajgräs och klöver. Analysen visade dock att det finns stora begränsningar med att använda dessa enkla standardmetoder för att mäta kolinlagring. Slutsatsen är att även om dessa metoder har stor potential att förbättra jordbrukets klimatnytta, så är de biologiska processerna i marken komplexa. Därför rekommenderar studien en "Hybrid LCA". Det är en metod som kombinerar data från hela leveranskedjan med specifika mätningar på plats för att mer exakt kunna fånga hur kolhalten i marken förändras över tid.

Nyckelord: FLAG, Nötköttsproduktion, Agroforestry, Växelbetesystem, Fånggrödor, Livscykelanalys, Kolinlagring.

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AGM	Above Ground Biomass
BGM	Below Ground Biomass
DMI	Dry Matter Index
FAO	Food & Agriculture Organisation
FLAG	Forest, Land & Agriculture
FU	Funtional Unit
GHG	Green House Gas
GWP	Global Warming Potential
HC	Heavy Continuous Grazing
HCMR	Heavy Continuous Grazing + Moderate Rotational grazing
IPCC	International Panel for Climate change
LC	Light Continuous Grazing
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCMR	Light Continuous Grazing + Moderate Rotational grazing
LMP	Land Management Practices
LU	Livestock Unit
LUC	Land Use Change
LW	Live weight
PEF	Product Environmental Footprint
PLF	Precision Livestock Farming
RG	Rotational Grazing
SBTi	Science Based Targets Initiative
SOC	Soil Organic Carbon

Glossary

Adaptive Multi -paddock grazing	*Another type of RG where grazing patterns are adjusted based on forage availability*
Agroforestry	*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms , bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence (Nair,P.K.R, 1993)*
Backgrounding	*Backgrounding refers to the grouping and adaptation of animals prior to entry into the feedlot or intensive finishing system.*
Carbon sequestration	*The long-term capture and storage of CO2 in carbon pools*
Cover cropping	*Grows specific crops to cover the soil*
Crop Rotation	*Alternates different crops in the same area*
Enteric Fermentation	*Methane* (CH_4) *is produced during the digestive process of cattle as microbes break down fibrous feed in the rumen.*
Feed production	*Activities related to the cultivation, harvesting, and management of crops and forage used to nourish cattle.*
Feed production	*Emissions arise from the cultivation, harvesting, processing, and transport of feed crops and forages.*
Feedback loop	*circular process where the output of a system re-enters as an input and influencing the future of the system.*
Land use	*Emissions due the change in land use like converting a forestland to pasture,etc.*
Pollution swapping	*Sajeev et al. (2017b) also states that reducing one pollutant might lead to increase in another which is called pollution swapping*
Rearing and Growth	*Management of reproductive processes in cattle, weaning and post-weaning stage, during which cattle are raised until they reach market weight*
Reduced Tillage/No tillage	*Managing Tillage to minimize soil disturbance*
Removals/ Carbon removals	*The process by which anthropogenic activities extract GHGs from the atmosphere and store them long term*
Rotational Grazing	*Moves livestock between different pastures*

1 Introduction

1.1 Background

Beef is one of the most significant sources of dietary protein, valued for its nutritional benefits (Hawley et al., 2022). The Beef supply chain contributes positively to the human diet, providing high quality nutrients that are crucial for health. However, its production is associated with substantial environmental impacts, particularly in terms of GHG emissions, driving the need for mitigation measures across the supply chain.

The emissions from beef production are generally categorized under emissions from FLAG Sector. FLAG sector is the third highest contributor of Global GHGs preceded by Energy and Industry sector. FLAG Emissions account for 22% of Global GHG Emissions (SBTi, n.d.). Within this high-impact sector, beef is considered one of the highest-impact commodities (IPCC, 2019) and is one of the nine key agricultural commodities identified by SBTi to set targets to align with the Paris agreement (SBTi Addendum, 2022). The livestock sector as a whole is responsible for around 14% of global anthropogenic GHGs, with beef production accounting for the largest single share of livestock emissions, approximately 41% (IPCC, 2019).

Addressing these emissions requires action across multiple fronts. Historically, the global demand for beef has driven deforestation for pasture expansion and feed production (Recanati et al., 2015). This LUC releases substantial amounts of sequestered carbon from above-ground biomass and soils, simultaneously diminishing the land's future capacity to act as a carbon sink. Furthermore, biogenic emissions from enteric fermentation in ruminants and nitrous oxide (N_2O) from manure and fertilizer use contribute significantly to the total climate footprint at the farm level.

The SBTi FLAG Guidance (2022) provides the framework for corporate climate action in this sector, introducing specific requirements to ensure climate targets are science-based and robust. The guidance fundamentally requires companies to:

- Account for and reduce FLAG emissions from their supply chains.
- Recognize carbon removals from land management
- Eliminate deforestation and restore degraded lands.
- Develop GHG inventories that include soil carbon, LUC, and non-CO_2 gases.

To guide corporates in setting these targets, SBTi has developed commodity specific mitigation pathways for its key agricultural commodities. Commodity pathways trace the environmental impacts associated with the production, sourcing, and land-use impacts of specific agricultural products. Commodity pathways are very helpful to understand how beef is produced across different geographies, to map land conversion driven by beef demand and to identify emission hotspots along the supply chain. This understanding aids in developing targeted mitigation strategies for each stage of production.

Given this context, the IPCC's Sixth Assessment Report highlights mitigation potentials emphasizing the importance of sustainable land management and soil carbon sequestration as essential tools for making an impact in the agriculture sector. This thesis aligns with these frameworks by assessing how improved land management practices in beef production, especially those rooted in regenerative agriculture, can help IKEA meet SBTi targets while also contributing to broader environmental goals like carbon neutrality, biodiversity conservation, and soil restoration. Due to these standards and guidelines, several organizations have already started implementing practices that mitigates the emissions and increasing the carbon stocking capacity of the land as conventional farming practices like monoculture, mechanization and use of fertilizer,.etc. increases soil health depletion and plays a major role in biodiversity loss (Villat & Nicholas, 2024). These types of land-use change not only releases substantial amounts of CO_2 but also reduces the soil capacity to sequester carbon, aggravating climate change. At the same time instead of LUC when the land is better managed, it has mitigation potential increases.

Given the background and substantial contribution to FLAG emissions, targeting the beef industry is crucial for effective climate action with a major strategy of improving Land management practices. The research aims to determine how these improved practices can help IKEA to formulate strategies for meeting FLAG targets while contributing to broader sustainability goals like carbon neutrality and soil restoration.

1.2 Aim & Objective

The aim of the master thesis is to identify and evaluate the potential of existing Land management practices involved in beef production in the market and implementing these practices within IKEA's beef supply chain to enhance sustainability. Conducted in collaboration with IKEA, this research supports the company's broader sustainability agenda by exploring how land management strategies can contribute to emission reductions and increased carbon sequestration. The research aims to provide insights to help make beef supply chains meet SBTi targets and support regenerative, climate-resilient food systems.

To refine the scope and provide targeted insights, the following research questions guide the study:

- What land management activities are available that can reduce FLAG emissions or enhance FLAG removals in beef production systems?
- To what extent can these identified activities reduce emissions or increase removals across different beef production systems and sourcing regions?
- Which combinations of land management practices are most effective in achieving specific climate goals related to FLAG emissions and removals?

2 Methodology

2.1 Literature review

Literature review forms a major part of this thesis to understand the state of the art of different land management practices in beef production systems. This section will summarize the current knowledge, methods, and gaps related to land management practices in beef production systems.

The key words used in discovering scientific articles from various research platforms like ScienceDirect, Google Scholar etc. are ”GHG emissions in beef Production”, “Beef Life cycle assessment/LCA”, “Environmental impacts of beef Production”, “Manure management in beef production”, “Technologies to reduce GHG emissions in Beef production”, “Beef production, supply chain”, Carbon sequestration in Beef production”, “Accounting for emissions/removal” along with guidelines like SBTi, IPCC, FAO etc. After searching the articles and journals using keywords, the selection of literature involved a filtering process (Funnel approach) with several steps. In the preliminary stage, the focus was on the commodity, inclusion of several LMPs, and date of publishment of the journal, preferably within the last 15-20 years. In the secondary stage, the main emission contributors were identified, and if the studies were evaluated, mitigation methods linked to those contributors were analyzed. Certain studies were excluded at this stage as they focused on mitigation options outside the land domain.   At the final stage, detailed analysis was carried out with literature that were methodologically comparable, if the studies were IPCC aligned, from different regions, that accounted for net emissions including removals.

2.1.1 Overview of Beef production systems

To understand land management practices in beef production, it is essential to first understand how the overall beef production system functions and the key processes involved. Although beef production includes a variety of systems (Greenwood, 2021), the core process flow remains largely consistent across them as shown in *Error! Reference source not found.*.

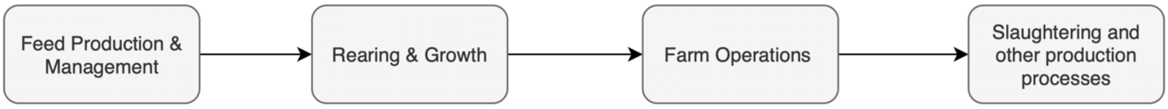


Figure 1 : Flow of Beef production system

Farm Operations refer the daily management activities required to support cattle and infrastructure, such as manure storage and application, water use, energy consumption, and equipment use (e.g., for fencing, lighting, or transport within the farm). Once cattle are slaughtered, the system shifts to downstream processes like processing, packaging, transportation, and distribution, where land use and land management no longer play a direct role. Environmental impacts in these stages are more related to energy and water use, refrigeration, and packaging.

Beef production systems globally exhibit considerable diversity and can fall into different categories based on their function, scale, feeding strategy and the relevant sources, cattle development, end product and market orientation (Greenwood, 2021) The different types of production systems are listed in *Error! Reference source not found.*. The environmental footprint of each of this system also varies, with trade-offs between GHG emissions, land use, and resource efficiency. Integrating sustainable practices is essential across all systems to mitigate environmental impacts and enhance the sustainability of beef production globally.The difference in environmental footprint of these systems i.e. the range of emissions & removal due to the different practices are the basis to comprehend the potential of each of these practices. Quantifying these differences enables a systematic approach to identify the root cause of the impacts caused by the system and point out mitigation strategies required to reduce emissions while simultaneously focusing on increasing carbon removals. Each LMP varies in the way they are implemented globally due to the difference in methodology regionally as well as the different environmental conditions. The different stages in the production of beef involves different types of land management which is again listed in th***e Appendix – II***. The next section is a summary of the existing practices and their potential in reducing emissions and increasing the carbon removal.

2.1.2 LMPs in Feed production & Pasture Management

Different LMP involved in the production of feeds and pasture management practices are explained here.

Agroforestry involves interactions of different species especially plants and livestock altogether hence it is a very complex system (Nair, P.K.R., 1993). There are different types of agroforestry systems based on the types and species that sustain in the same land area. Carbon sequestration rates are different in different agroforestry systems but overall, they show significant increase in long term Soil Organic carbon. According to Torres et al. (2017), Agroforestry systems can potentially offset emissions up to 100%. Monteiro at al. (2024) shows a biogenic carbon uptake of up to 36 kg CO_2e / kg LW. Agroforestry system proves to be the most significant natural solution for increasing removals by improving soil fertility, water quality and reducing erosion thereby helping in the rehabilitation of degraded land (Torres et al.,2017). However, implementing agroforestry systems might require huge investment that also gives long term gains whereas conventional pasture systems involve short term costs and returns (Monteiro et al. 2024).

Cover cropping with diversified crop rotations are a significant strategy that reduces emission and increase removals. The use of cover crops extends to two areas in beef production: they are integrated into the crop rotations that supply feed to feedlots, or they are established directly on grazing lands to enhance soil and forage quality. Cover crops can sequester carbon by providing above and below-ground biomass. Drinkwater et al. (1998) showed that legume-based cover cropping reduced nitrogen losses compared to high fertilizer systems because of their Nitrogen fixating properties (O'Brien et al., 2023). Here it is crucial to understand that few of these practices have synergistic effects, meaning their combined impact could be greater than the individual impact. Long term field trial in Brazil studied by Da silva et al. (2025) found that no till systems with winter cover crops could reduce upto 100% emissions compared to bare-fallow systems. Cover crops also present a chance for double benefits in beef systems. Certain cover crops like annual ryegrass, turnips, or oats can be grazed by cattle in the off-season, providing cheap forage while still protecting soil (ANSI 3298, OSU).

Using Mixed swards like legumes in Pastures can reduce GHG emissions in grazing systems. Integrating legumes in the pasture reduces the synthetic Nitrogen fertilizer usage since nitrogen is fixed organically by the legumes (O'Brien et al., 2023). Subsequently the animal performance also increased due to this integration (O'Brien et al., 2023). By introducing other better forage species and managing the pasture, Pelletier et al. (2010) shows that the emissions reduced from 22.5kg CO_2 eq to 9.2 kg CO_2 eq per kg of LW showing a potential of 60% reduction in the emissions. Therefore, managing pasture using multiple species improves productivity at the same time reducing the fertilizer driven emissions.

Grazing management practices can be of different types as mentioned in ***Appendix – II***. RG or AMP is one of the commonly employed grazing management. RG can enhance the health of pasture by improving the forage quality and yield along with increased animal efficiency (Stanley et al., 2018). This improvement in soil health eventually led to increased carbon sequestration by increasing the soil Organic carbon. Stanley et al. (2018) shows approximately 3.5 Mg C/ha/yr soil carbon increase. In the same study, the results show that well managed grazing can offset significant amount of emissions through carbon storage even though the feedlot-based production showed less emissions. When the pasture is well managed, soil microorganisms and other habitat support and develop healthier and diverse swards. A factsheet from Oklahoma State university states that the climate impact would be substantial even if a fraction of global grasslands could increase soil Carbon (ANSI 3298, OSU). However, the challenge of RG is mainly related to the management and labor intensive since it involves movement of cattle and careful planning of changing paddocks especially in AMP grazing. RG also largely depends on climate and soil type. Therefore, in rotational grazing, proper management in planning the paddock and managing the grazing is the critical component.

2.1.3 LMPs in Manure Management

Livestock manure is a significant source of NH3 and other GHGs, including methane and nitrous oxide (Sajeev et al., 2017b). Manure management contributes to about 10% of Global livestock emissions (CGIAR, 2023). Anaerobic digestion that occurs in uncovered liquid manure storage is a major source of CH_4 (Baldé et al., 2016). Covering pits/lagoons and capturing the biogas (methane) for energy use is a very effective way to reduce these emissions. Cusack et al.,2021 reaffirms the effectiveness of covered manure storage for CH_4 reduction.

Another common practice in manure management is Direct injection or targeted application of manure. This process reduces the surface area exposed to the atmosphere, minimizes ammonia volatilization which reduces the amount of nitrogen available for denitrification and nitrification, the processes that produce N_2O (De Vries et al., 2022). This process can reduce 10-25% N_2O reduction from more efficient usage of nutrients (De Vries et al., 2022).

Ryals et al. (2014) Showed that composting manure reduces CH_4 and improves soil Carbon sequestration. Composting process is mainly aerobic; therefore, it largely prevents the anaerobic process which prevents CH_4 production in the covered pits or lagoons. CH_4 reduction from well aerated composting compared to stockpiling which is anaerobic is often greater than 50% (Ryals et al., 2014).

Nonetheless, managing the pollution swapping created during these process remains a challenge. Sajeev et al. (2017b) studied 8 different abatement options among which only 3 reduced NH_3, N_2O, and CH_4 emissions simultaneously. The study specifically shows that Covers for Manure Storage reduced NH_3 (65%) and CH_4 (11%) however increased N_2O emissions (over 500%). Similarly Shallow Injection of manures significantly reduced NH_3 (71%) but generally increased N_2O emissions (259%). This shows that manure management needs a holistic approach that can assess the effect of all pollutant gases simultaneously in manure management rather than focusing on reducing one particular gas which might eventually increase the emissions

2.1.4 Precision Livestock Farming (PLF) & Data-Driven Strategies supporting LMPs

The integration of technology and data-driven tools in cattle farming is transforming the sustainability of beef production. Precision farming does not seem like direct management of land but these tools are a significant improvement in LMPs. Precision Livestock Farming (PLF) includes technological innovations such as electronic identification, sensors, drones, GPS-enabled collars, automated feeding systems, and decision-support software. These technologies enable real-time monitoring of animal health, feed intake, pasture conditions, and manure application, which enhances both productivity and environmental performance. (McNicol et al., 2024, Papakonstantinou et al., 2024)

Here is a summary of different technologies used in PLF and their relevant impact in beef production.

Table 1 : Summary of Precision Livestock farming

Technology	Impact created	Reference
Smart feeding systems like Automated weighing platforms	Improved feed efficiency and reduced waste	McNicol et al., (2024)
Wearables (health sensors) or AI-based system for the cows	Early disease detection and health monitoring reducing the use of resource-intensive treatments.	Rutten et al., (2013)
Remote sensing and virtual fencing	Optimized pasture management that prevents overgrazing and enhances soil carbon sequestration.	Elvidge et al. (2021)
Aggregating performance data	Precision breeding improving herd efficiency resulting reducing emissions per kilogram of beef.	Caja et al. (2016)
Nutrient mapping tools	Better manure and fertilizer management by minimizing nitrous oxide (N_2O) emissions.	Caja et al. (2016)
Variable Rate Technology (VRT), GPS-guided applicators, and drones	Improve input efficiency and reduce environmental impact	Papadopoulos et al. (2024)

In beef systems, all these technologies listed above aim to optimize pasture fertilization and forage production, thereby indirectly improving cattle performance. Precision farming can lower greenhouse gas emissions from beef operations by improving efficiency. For example, a modeling study in Scotland found that adopting PLF tools like automated weigh scales and health sensors reduced total beef GHG emissions by 4–6% in grazing-based systems, and up to 6–12% per unit of beef output. (McNicol et al., 2024). Site-specific fertilizer application avoids over-application of nitrogen, which curbs nitrous oxide (N_2O) emissions and CO_2 from fertilizer manufacturing. Research indicates that precision fertilizer management can reduce nitrogen fertilizer use by 10–20% while maintaining yields, directly translating to lower N_2O emissions.

2.2 Emission contributors and Mitigation Measures

One of the primary objectives of this research is to find potential ways to reduce GHG emissions and increase removals through LMPs. As elaborated in the preceding sections, the global diversity in LMP implementation, driven by regional methodological variations and distinct environmental conditions, results in considerable difference in their emission reduction and carbon sequestration potential. Consequently, a comprehensive analysis to quantify emissions of LMPs across every stage of beef production is inherently extensive and poses analytical challenges. However to simplify the challenge and to more effectively identify the mitigation measures, based on the detailed Literature review conducted a summary of emission reduction potential using different practices is summarized in the ***Table 2***, Along with the potential the major emission contributing categories in all the literatures were listed. The four major emission contributors are shown in ***Figure 2.*** Enteric Emissions or emissions from enteric fermentation is the digestive process in ruminants that release large amounts of methane. Other categories include emissions from feed production, manure and other Land use changes.

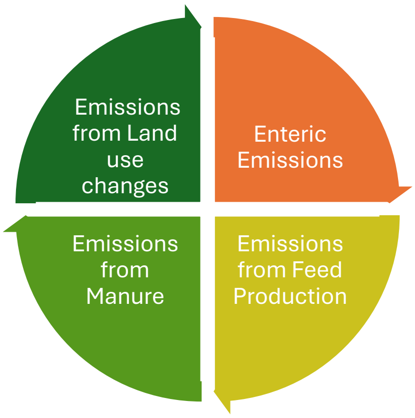


Figure 2 : Major Emission Contributors in Beef Production

Research consistently identified enteric fermentation as the primary driver of livestock emissions, typically accounting for 50% to over 65% of the total footprint. Feed production represents the second-largest category (20–30%), consisting of crop cultivation, fertilization, energy use, and logistics. While manure management and land-use change generally contribute 10–15% each, these figures fluctuate based on regional practices. Manure emissions are dictated by the specific storage system used (e.g., slurry vs. composting), whereas land-use impact depends on whether the study accounts for deforestation or pasture expansion. Notably, a paradox emerges in extensive pasture-based systems: while they may reduce secondary operational footprints, they often result in significantly higher enteric emissions per animal. Graphical representation of how these emissions are distributed across different literatures are shown in ***Figure 3*.**

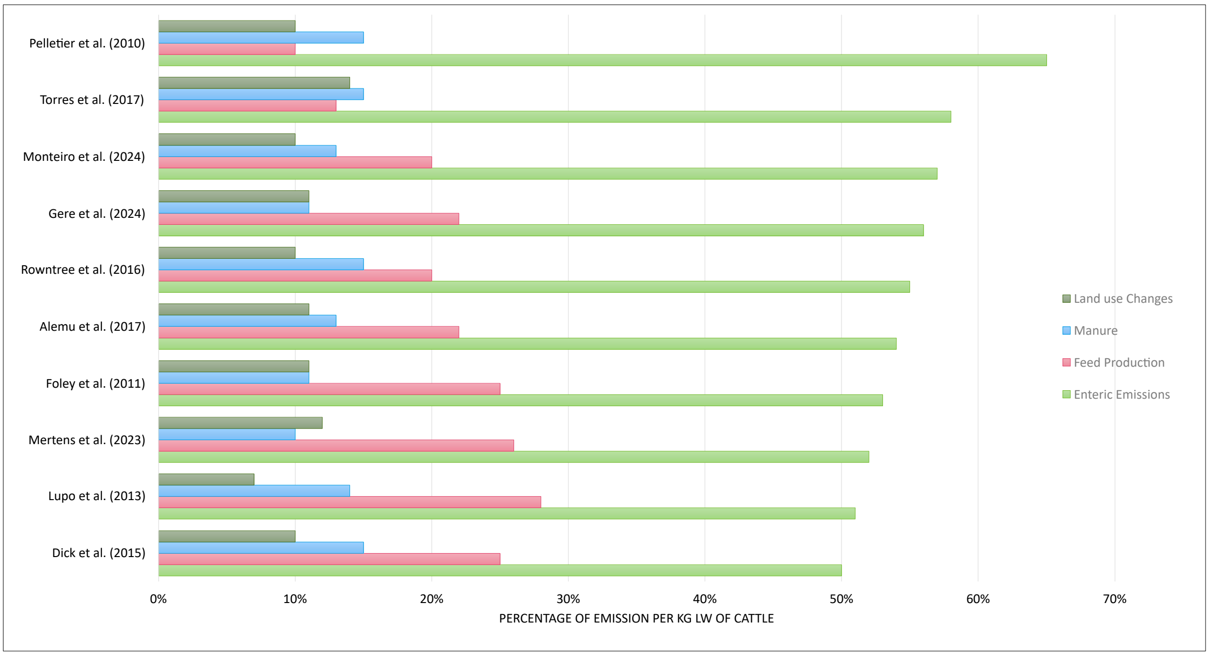


Figure 3 : Summary of Emission Contributing Categories from different literature

The various mitigation methods include integrating changes in Land management and farming systems. The high-level summary of the most common mitigation measures identified across the literature for each major emission category in beef production include measures for enteric emissions that mainly focus on dietary interventions of including microalgae, synthetic inhibitors, fats, tannins, and other feed additives. These approaches aim to directly reduce methane formation. (Purba & Sangsawad, 2025, Dick et al. (2014)) Many studies show promising reductions, but the effectiveness varied by inclusions in diet, breed of the cattle, and overall components of a production system. As mentioned before Feed production emissions come from fertilizers, energy and fuel on and off the farm. Mitigation strategies therefore target management of crop production and the pasture as well as the grazing. These not only reduces emissions but also supports soil carbon gains. Therefore, reduce the net emissions. (Dick et al. (2014); Cusack et al. (2021)) This mitigation measure also indirectly affects the Enteric emissions. Mitigation options for emissions from manure include better manure storage and handling, reducing anaerobic conditions, and using anaerobic digestion to capture methane for energy (Wang et al. (2021); Sheppard et al. (2016)). For land use changes, two major mitigation routes emerge, integrating agroforestry to increase carbon sequestration and diversify land use. Avoiding land conversion particularly deforestation which is one of the largest single contributors to LUC emissions (Torres et al. (2017); Monteiro et al. (2024))

Based on the analysis on mitigation measures***, Table 2*** shows the different ranges of emissions from various production system when different LMPs are integrated to mitigate emissions. Emission ranges lie between 14-33 kg Co_2e / kg LW for a mixed system. Pelletier et al. (2010) reported the lowest emissions for a mixed system utilizing early finishing and hormonal implants. The shortened finishing period reduced total feed requirements and associated emissions, particularly from feed production and manure management. The case study by Lupo et al., (2013) shows emission of 23 kg Co_2e / kg LW for the same type of production. The difference in these two studies is mainly due to the number of days spent in pasture and the ratio of concentrate to forage in these two systems.

In contrast to the conventional system, Monteiro's case study (2024) which integrated agroforestry found higher emission intensities in a system employing extended pasture finishing. However, it is important to note that this system also demonstrated substantial increases in soil carbon stocks, which contribute to long-term carbon sequestration and therefore offset the higher gross emissions. These findings highlight systems that appear emission intensive at the production level may also deliver substantial climate benefits when soil carbon sequestration is factored in. Torres et al. (2017) showed the lowest range of emission in 4 years which is a Silvopastoral system with eucalyptus trees integrated in the pasture. It can be noticed that the emission is very low compared to other systems. This is due to no-till farming and adoption of agroforestry systems with reduced machinery, fuel emissions. The simplified system reduced upstream emissions while benefiting simultaneously from the cumulative carbon uptake of both trees and soil.

Rotational grazing practices in the studies showed consistently same range of emissions even with different types of rotational grazing. Stanley et al. (2018) showed carbon sequestration potential of 3.59 MgC/Ha/yr. The AMP system here points out the short duration, high intensity grazing with longer resting periods results in optimal forage regrowth enhancing SOC storage which reiterates the fact that improving the carbon sequestration can bring down the net emissions. Different RG systems like HCMR & LCMR resulted in less variation in GHG emissions showing that simply combining continuous and moderate rotational grazing in a hybrid form might not be sufficient to change carbon balances or reduce emissions unless combined with better forage utilization. According to Alemu et al. (2017), the HCMR system still retained relatively high methane emissions due to the heavy stocking rates and diet composition, with soil C sequestration rates ranging only between 0.01 and 0.46 Mg C ha^{-1} yr^{-1}. These rates are substantially lower than those achieved in AMP systems, indicating the importance of grazing rest periods and adaptive stocking management for climate benefits. When the different systems are compared without considering SOC, all these practices fall in a range of approximately 13–16 kg CO_2e/kg LW. These results reinstate the fact that while all rotational grazing systems can maintain emissions within a manageable range, only managed grazing systems like AMP have the potential to function as a net carbon sink, making them a high-impact land management practice. However, the impact is positive only when the pasture is managed precisely, including optimal paddock rotation intervals, appropriate stocking densities, and adaptive responses to pasture biomass.

Cover cropping systems demonstrate huge potential to reduce greenhouse gas (GHG) emissions in beef production, especially when diverse mixtures are employed, GHG emissions vary significantly across different cover cropping configurations. The highest emissions were associated with cover crops combined with winter fallow, largely due to the absence of photosynthetically active cover during critical periods, leading to lower carbon inputs and greater soil nitrogen losses. This is in with the findings of Silva et al. (2025), who observed that winter legume-based cover crops (oat-vetch systems) exhibited higher N_2O emissions compared to summer species due to increased nitrogen turnover in colder, wetter conditions whereas cover crops with vetch, ryegrass, and forage radish showed some of the lowest emission intensities, almost half that of the winter fallow system. Gere et al. (2024) demonstrated that grazing cattle/steers on mixtures of leguminous and non-leguminous species (vetch + ryegrass + radish) led to a 29% reduction in enteric methane and 36% lower CH_4 yield compared to traditional alfalfa–fescue pastures. The methane reduction is largely attributed to higher dry matter digestibility, lower fiber content and improved nutrient quality in these mixed cover systems. (Gere et al., 2024). In addition to the above, Silva et al. (2025) highlights the benefits of summer cover crops like lablab and pigeon pea, showing they can even result in negative net GHG emissions under no-till conditions due to robust soil carbon sequestration, which more than offsets their relatively modest N_2O and CH_4 emissions. However, implementing cover crops is influenced by range of biophysical and management factors, including soil type, climate, crop species, and duration of the cover. In contrast, in arid or high-latitude regions with short growing seasons, establishing cover crop might be failing or yield least biomass. (Da Silva et al., 2025; Gere et al., 2024). Da Silva et al. (2025) observed that systems with two legume cover crops per year exhibited higher N_2O emissions than winter fallow systems, illustrating the risk of “pollution swapping” where gains in CO_2 sequestration are offset by increases in other GHGs.

Table 2 : Emission Quantification based on Literature Review

Sl.no	LMP	Study	Region/ System	Model/ Method	Baseline Scenario	Improved Scenario	GHG per kg LW (Baseline)	GHG per kg LW (Improved)	Reduction (kgCO2e, % of Reduction)	Carbon removals
1	Mixed production systems with no specific LMP	Pelletier et al. (2010)	Upper Midwest, USA	ISO-compliant LCA using IPCC Tier 1–2 for CH_4/N_2O, cradle-to-farm gate	Grass-finished beef	Feedlot-finished beef	19 kg CO_2e	14.15 kg CO_2e	4,85 (25%)	-
2	Mixed production systems with no specific LMP	Wiedemann et al. (2014)	Australia	National Inventory comparison	1981 extensive, mostly pasture fed	2010 improved pasture + Feedlot	15.3 kg CO_2e	13.1 kg CO_2e	2.20, (14%)	-
3	Steer vs Earlier finishing	Foley et al., 2011	Ireland	Whole farm simulation	Castrated males finished as steers	Uncastrated bulls finished faster	22 kg CO_2e	19 kg CO2e	3 (14%)	-
4	Agroforestry (Agrosilvopastoral)	Monteiro et al. (2024)	Amazon biome, Brazil	Field trial, 4-year ecosystem C balance	Pasture -13.12 kg CO_2e Livestock forestry (Pasture + Eucalyptus) – 14.73 kg CO_2e Crop-Livestock (Soybean + corn+ pasture) – 9.85 kg CO_2e Crop Livestock forestry (CL + Eucalyptus) – 10.83 kg CO_2e				Net negative emissions	56,5 to 81 Mg CO_2e/ha in 4 years

Sl.no	LMP	Study	Region/ System	Model/ Method	Baseline Scenario	Improved Scenario	GHG per kg LW (Baseline)	GHG per kg LW (Improved)	Reduction (kgCO2e, % of Reduction)	Carbon removals
5	Agroforestry (Agrosilvopastoral)	Torres et al. (2017)	Southeast Brazil, Tropical Pasture	IPCC-based LCA, field biomass monitoring	Agrosilvopastoral system (S1 & S2) Vs Silvopastoral system (S3 & S4)		S1 (Maize+Eucalyptus) - 14.12 kg CO_2e S2 (Beans+Eucalyptus) – 7.52 kg CO_2e S3 (Pasture+Eucalyptus) – 7,15 kg CO_2e S4 (Pasture+Eucalyptus) – 4.97 kg CO_2e		Up to 100% offset	10 - 58 Mg CO_2e/ha in 6 years
6	Crop Rotation + RG	Dick et al. (2015)	Southern Brazil	Whole-farm LCA, IPCC Tier 1/2 + SOC dynamics, 20-year simulation	Extensive Pasture	Rotation with Winter forage pasture and RG	22.52 kg CO_2e	9.16 kg CO_2e	13,36 (60%)	
7	Cover Cropping + No till	Da Silva et al. (2025)	Southern Brazil	Field trial, LCA	CC cropping with winter fallow	CC with Oats & vetch	20 kg CO_2e	22 kg CO_2e	10%*	0,16 to 0,43 Mg C/ha/yr
8	Cover Cropping + No till	Da Silva et al. (2025)	Southern Brazil	Field trial, LCA	CC with Pigeon pea	CC with Lablab	20 kg CO_2e	21 kg CO_2e	5%*	0,55 to 0,86 Mg C/ha/yr
9	Cover cropping	Gere et al. (2024)	Argentina	Field trial	Alfalfa & Fescue pasture	CC with vetch,ryegrass & Forage radish	11,69 kg CO_2e	10,63 kg CO_2e	1,06 (9%)	-

Sl.no	LMP	Study	Region/ System	Model/ Method	Baseline Scenario	Improved Scenario	GHG per kg LW (Baseline)	GHG per kg LW (Improved)	Reduction (kgCO2e, % of Reduction)	Carbon removals
10	AMP Grazing	Stanley et al. (2018)	South Africa	Comparative LCA, cradle-to-farm gate	Feedlot finishing	AMP grazing	14 kg CO_2e	15 kg CO_2e	6,7%*	3,59 Mg C/ha/yr
11	RG	Alemu et al. (2017)	Western Canada	HOLOS LCA, Tier 2	Different types of RG (LC, HC, LCMR & HCMR)		LC – 15,95 kg CO_2e HC – 14.48 kg CO_2e LCMR – 14,84 kg CO_2e HCMR – 14.30 kg CO_2e		-	0,01 – 0,46 Mg C/ha/ yr
12	RG	Mertens et al. (2023)	Germany	Bio-economic farm model + LCA	Conventional grazing	Fast RG	14 kg CO_2e	13.5 kg CO_2e	0,5 (3,6%)	-
13	Grazing Management	Lupo et al. (2013)	Northern Great Plains, USA	Whole-farm LCA with IPCC Tier 2 CH_4/N_2O, SOC change included	Grass-finished in native pasture	Feedlot-finished with improved pasture	32 kg CO_2e	23 kg CO_2e	9 (28%)	-

The initial strategies listed in the table focus on optimizing production cycles to reduce emission intensity. Pelletier et al. (2010) and Wiedemann et al. (2014) demonstrate that optimizing confined feeding and transitioning to improved pastures can reduce emissions by 14% to 30%. Similarly, Foley et al. (2011) highlights a biological lever, finishing uncastrated bulls faster than castrated steers, resulting in an 18% reduction in lifetime emissions. These measures are critical for lowering the emissions but do not directly attribute to managing the land. The most transformative results are found in integrated systems where emissions reduction is secondary to massive carbon removals as seen in Monteiro et al. (2024) and Torres et al. (2017). These systems can achieve net-negative emissions, with larger sequestration rates as mentioned above.

Cover cropping and crop rotation (e.g., Da Silva et al., 2025) serve as primary soil health strategies. By increasing organic matter input and utilizing no-tillage to prevent carbon release, these practices stabilize the soil sink (0.16 to 0.86 Mg C/ha/yr), even if machinery inputs slightly raise gross emissions. The data suggests that while Rotational Grazing (RG) is a foundational managed practice showing steady but modest improvements (3.6% to 13% reduction), it is often outpaced by more intensive systems. Notably, Stanley et al. (2018) illustrates a critical trade off where AMP grazing may increase enteric emissions per animal, yet it provides a substantial net climate benefit due to high carbon removal rates. The central takeaway from this analysis is that the ultimate environmental benefit in beef production is not found solely in minimizing gross emissions, but in maximizing the carbon removal potential of the agroecosystem. By shifting the focus from low emission efficiency to high-sequestration transformation, livestock systems can move toward a positive net climate outcome where soil and biomass removals neutralize or exceed biological emissions.

3 Case study

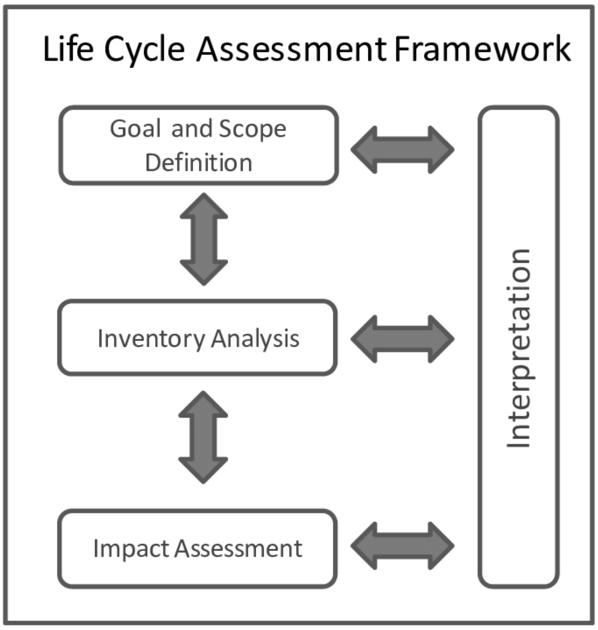
To address the research question concerning the mitigation and removal potential of specific activities within the IKEA beef supply chain, LCA methodology is adopted to simulate the identified LMPs on a representative existing farm. Based on the literature study above regarding the mitigation potential and ease to implementation While Agroforestry was initially selected as one of the LMPs, its complex component interactions proved challenging to model accurately under existing data and time constraints. Consequently, the scope was refined to focus exclusively on the implementation and quantification of RG & CC in the case study.

Life cycle assessment is a standard methodology used by experts to quantify different environmental impacts. Different studies in literatures also showed LCA as a methodology to quantify emissions which is also expressed in Table 2. The tool used in this study is Simapro, a life cycle analysis tool commonly used for estimating emissions and studying impacts.

Due to the unavailability of primary data, the data used in the study is completely based on secondary farm data from Casey and Holden (2006) and Agri footprint 2022. The location of the farm is in Ireland which is one of IKEA's sourcing regions.

3.1 Life Cycle Assessment

Life cycle assessment framework involves steps as indicated in the **Error! Reference source not found.**



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3.1.1 Goal of LCA

To quantify the changes in the emissions and carbon removals by integrating the selected LMPs rotational grazing and cover cropping in the Conventional beef production system.

3.1.2 Functional Unit

The functional unit chosen here is 1 kilogram LW of beef cattle at farm exit gate as the output produced through any type of production system is beef. This is different from the live weight of beef which includes the inedible components like bones, skin and other by products which are not essentially the final product of the commercial beef production system.

3.1.3 Intended application

Identifying effective LMPs to be used as mitigation strategies in beef production to lower the IKEA's overall climate impact is the main intended application of the study. Beyond applications to IKEA, the study also has broader application in academic research in the field of sustainable agriculture and LCA. It can also provide insights for organizations that have the requirement to switch to regenerative agricultural practices to mitigate emissions and in the development of policy making.

3.1.4 Intended audience

The intended audience include IKEA and the internal stakeholders at IKEA who use data to meet the climate targets and reach strategic decisions. The findings will also be helpful to beef producers and farmers in understanding and implementing regenerative practices.

3.1.5 Reference flow

The reference flow is the number of components required for producing 1 kg of beef cattle.

3.1.6 System boundary

This study focuses specifically on land use, related emissions, and soil carbon dynamics, restricting the system boundary from cradle to farm gate.

The system boundary includes upstream activities such as grass production which includes land occupation and energy use, water use, manure and housing management, and transportation of feed inputs. Emissions from enteric fermentation are considered, while production of concentrated feed is excluded except for its transport to the farm. Infrastructure and labor are excluded from the boundary. Studies shows that Infrastructure contributes very little (less than 2%) to total GHG emissions or other impacts in animal production systems. (Nguyen et al., 2010; Opio et al., 2013)

3.1.7 Assumptions

The following are the list of assumptions considered for the assessment.

1. The pastures are permanent grasslands so there are no LUC emissions considered for the past 20 years.
2. The system is assumed to be a suckler cow system, where cows are solely bred for the raising calves for beef production. The farm does not engage in any milk production, and all outputs are directed toward meat production.

3. Feed for the cattle is sourced domestically.
4. Construction and maintenance of farm infrastructure is excluded from modelling as they have only negligible contribution to emissions compared to major emissions and the inputs and outputs required are assumed to be same in all scenarios and thereby not influencing the comparison.
5. when the cattle is on pasture, the manure produced will be directly deposited in the pasture.
6. Three types of Manure management systems are assumed – Liquid slurry, Solid storage, direct excretion on Pasture (IPCC,2019).
7. Considering SOC equilibrium for baseline as there is scientific uncertainty on how long pastures continue to sequester carbon after initial improvements (Pelletier et. al.,2010) .
8. No Fertilizer usage, No irrigation, No pesticide in the land for the past 5 years and emissions from these are not accounted (Stanley et al., 2018) for scenario where rotational grazing is implemented in Scenario 2.
9. For cover cropping inclusion is Scenario 3, it is assumed that all biomass shall be decomposed on-site .
10. No ploughing and use of shallow cultivation equipment used in case of reduced tillage (Sørensen et al., 2014)
11. NPK fertilizer application rate is the same as conventional tillage (Sørensen et al., 2014)
12. The crops used in cover cropping replace silage from grass during winter.
13. While estimating carbon removals, the estimation of carbon stocks from Dead Organic Matter (DOM) is not included. As the IPCC method tier 1 & 2 requires specific, detailed quantification of dead wood biomass (both coarse and fine dead wood). The study area comprises grazed pasture and associated hedgerows which contains negligible or zero volume of standing or fallen dead wood. Therefore, the data requirements for a Tier 2 calculation are deemed impractical and inappropriate for this specific land management system.

3.2 Life cycle inventory:

The development of the inventory for this study began with preliminary efforts to collect primary data. However, due to the limited availability of specific and relevant primary information, the inventory was constructed using secondary data sourced from Agri-footprint 2022 database and literature.

The default model in Agri-footprint is based on a herd comprising three cows and fifteen two-year-old calves, assumed to be slaughtered after a lifetime of 730 days. This model, initially developed using data from Casey and Holden (2006), forms the basis of the inventory. The model consists data for beef produced in one cycle by a production system that combined pasture-based production with finishing through feed supplements.

For each scenario analyzed, adjustments were made to the default model to account for specific assumptions and to simplify the modeling process. The detailed modeling process for each element in all scenario remains consistent with the existing Agri-footprint database and is provided in ***Appendix – VI.***

The components of the system and their boundaries are shown in ***Figure 4*** in this section.

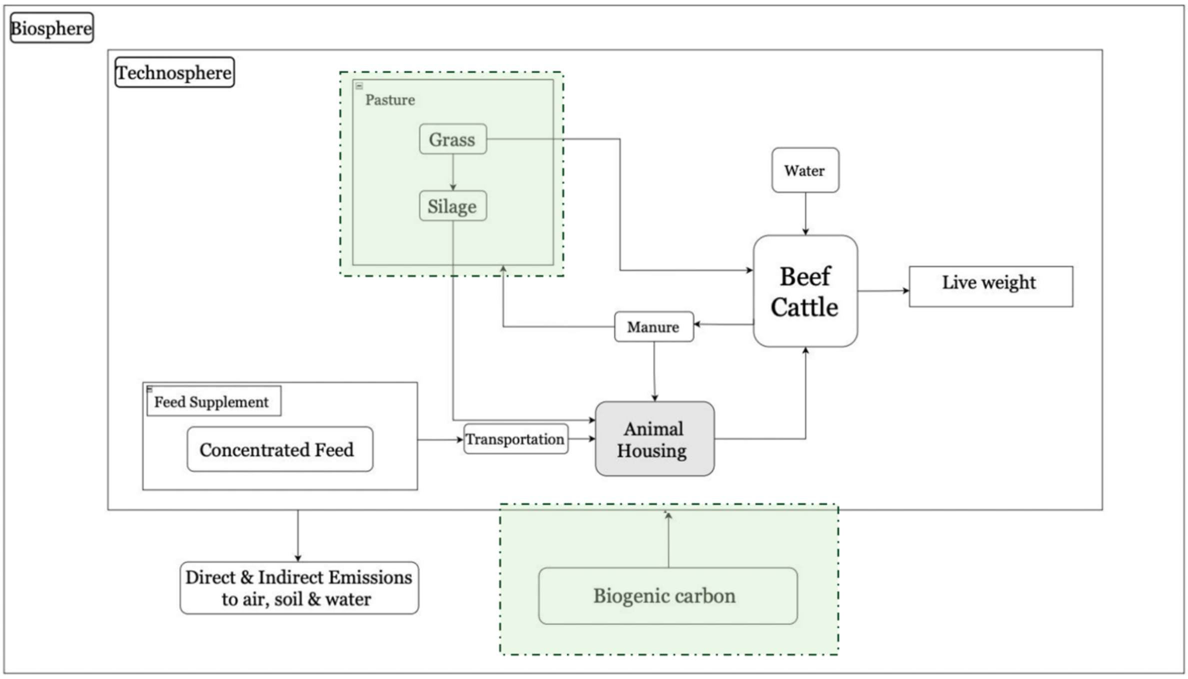

Figure 4 : System boundary

3.2.1 Baseline data:

The entire lifetime of the cattle in is 730 days. The cattle are weaned for the initial 184 days. Post weaning the cattle is fed concentrate and silage for the next 30 days outdoors and then the concentrate feed is provided inside the stable during the winter for 151 days. During the next 214 days the cattle is grass fed extensively in the pasture and finished using the combination of concentrate feed and silage for 151 days. These conditions are the same in the default model. However, to make the emissions specific to the farm conditions, CH_4 and N_2O emissions were recalculated using IPCC.

However, the methane and Nitrous oxide emissions estimated through IPCC Tier 2 methodology is found to be higher than the ones in the existing model and were found to be different from emissions represented through several literatures. This methodological discrepancy, also noted by Wu et al. (2024) and studies from ILRI (CGIAR), underscores a critical recommendation that emission calculations must always be validated with regional, site-specific data to reduce uncertainties.

3.2.2Rotational Grazing

Based on the results from literature review, Rotational grazing is integrated in the baseline as a grazing management practice replacing continuous grazing in pasture in the baseline.

In this system, cattle are regularly moved between different paddocks. To determine the optimal number of paddocks, the three-leaf assumption.ie., the time taken for three leaves to grow be the maximum grazing interval (Chapman et al., 2011). This period allows the forage to reach its third-leaf stage, offering both optimal nutritional quality for animal health and promoting sustainable pasture growth (Chapman et al., 2011 & Clarke et al., 2021). Since a single leaf takes approximately 7 days to grow, a three-leaf stage requires 21 days (Teagasc, 2020).

Following the findings of Stanley et al., (2024) and Chen et al. (2017), who indicate that high-intensity rotational grazing boosts below-ground carbon stocks, high-intensity, short-duration rotational grazing system with a 3-day residency period per paddock is implemented here.

The number of paddocks needed is calculated by,

$$\text{Number of Paddocks} = \frac{\text{Rotation Length}}{\text{Residency Time}}$$

This ensures enough "grazing slots" for continuous cattle movement while allowing pastures adequate recovery time. Based on this, it was determined that 7 paddocks are required.

Table 3 outlines the specific parameters for the rotational grazing system.

The model for the Beef cattle for slaughter at the farm Irish is the same as the baseline. However the grass for cattle in managed through rotational grazing. Based on the rotational period and residency time, the parameters for Rotational grazing is tabulated here in
Table 3.

Table 3 : Parameters for Rotational Grazing

Description	Quantity
Number of paddocks	7
Targeted LW of cattle	647 kgs
Dry matter intake (per cattle)	12.94 kg/day (2% of the body weight of the cattle (Casey & holden, 2006))
Total dry matter required for the entire herd	12.94 x 18 – 232.92 kg DMI/ Day
Area of each paddock	2.43 ha (17 hectares/ 7 paddocks)
Mean Stocking density (No of cattle/ area)	1.02 LU/ha

To simplify the model, active and rested paddocks were integrated into a single process based on their proportional time of use throughout the year. One paddock remains active for 30 out of 214 days, while the remaining paddocks are in resting phase for 184 days. This corresponds to approximately 14% active time and 86% rest periods.

3.2.3Cover cropping

In countries like Ireland, the temperate moist (IPCC, 2019) climatic conditions prevent year-round grazing, making it impractical for cattle to remain on pasture for all 365 days. As described in the baseline scenario, cattle are housed indoors and fed in stables for 151 days during the winter months of the first year and again during the finishing phase in the second year. This results in the land being left as bare fallow during winter.

In Scenario 2, the pasture is converted to a specialized cover cropping system that is evaluated through a Multi-Criteria Decision Analysis (MCDA) framework, as established by Sharma et al. (2018) and Jannoyer et al. (2011). This approach replaces grassland with a strategic rotation of oats and a mixture Ryegrass and red clover. The farming is characterized by a transition to reduced tillage to enhance soil organic matter retention organic inputs are utilized for the oat crop, while synthetic fertilizers are applied to the ryegrass and clover mix. The MCDA selection process prioritizes specific parameters, including nitrogen fixation capacity, biomass yield, cold hardiness, and trampling resilience, along with livestock-specific metrics such as crude protein content and digestibility for cattle nutrition.

The annual cultivation cycle is strictly timed to optimize ecosystem services and forage production: oats function as a winter cover crop from November through February to prevent nutrient leaching and soil erosion. Following the termination of the oats in March, the regrowth of the red clover-ryegrass is prioritized. The primary production phase occurs between April and August. This cycle concludes with mechanized land preparation in September, leading into the subsequent sowing of the oat crop in October to again establish the protective winter rotation with oats.

4 Results & Analysis

This section presents the resulting emissions by implementing the selected LMPs on the baseline conditions and highlights the hotspots. Consequently, contribution analysis is conducted to understand the root cause of the hotspots. The method of assessment used here is the IPCC GWP 100 (Including removals) method. The IPCC 2021 GWP100 was introduced in the Sixth Assessment Report (AR6) and it provides a standardized measure of the climate impact of GHG by expressing them in terms of CO_2 equivalents over a 100-year horizon. As a single-indicator approach, GWP100 aggregates all GHG emissions into a common unit of kg CO_2-eq, making it one of the most widely applied method in GHG accounting.

Figure 5 presents the results for the three modeled scenarios, expressed across three categories of climate impact: GWP100 from fossil sources, GWP100 from biogenic sources, land transformation. The findings indicate that the baseline scenario generates approximately 19 kgCO_2eq GHG per kg LW of Beef. Implementing rotational grazing reduces these emissions by about 13%, bringing them down to 16.5 kgCO_2eq per kg of LW. Similarly, the cover cropping scenario results in a decrease of about 7% with emissions of 18 kgCO_2eq.

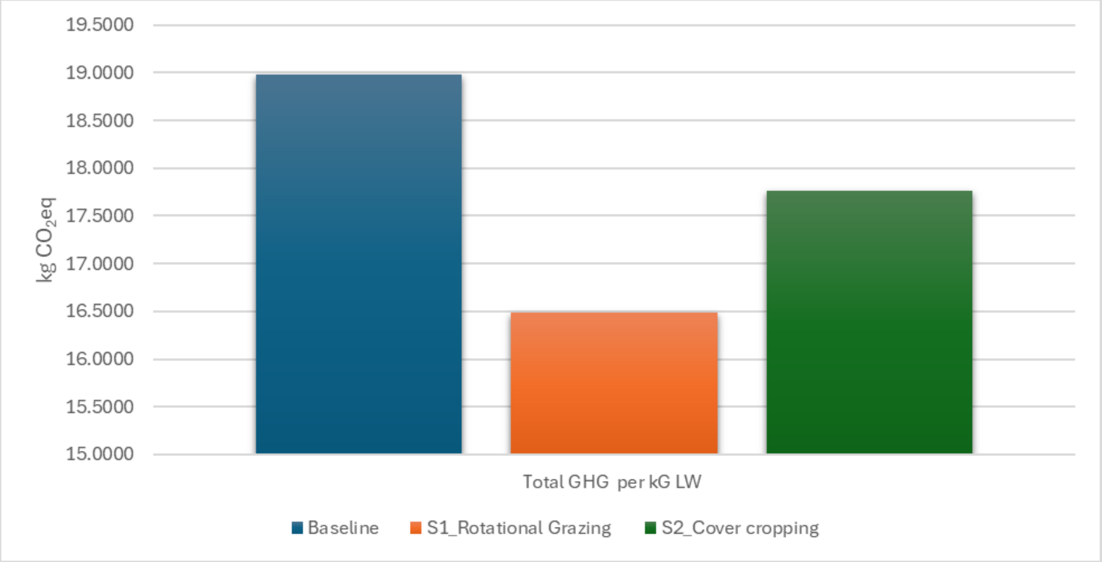

Figure 5: Comparison of GHG of the 3 different scenarios

Figure 6 illustrates the different components of the three modeled scenarios: Baseline, Rotational Grazing, and Cover Cropping.

In the Baseline scenario, the largest share of emissions is from the cattle themselves (53%), primarily reflecting biogenic emission, i.e Emissions from Enteric fermentation, followed by grass grazed in pasture (15%) and grass silage (15%). Compound feed contributes around 7%, with smaller shares from diesel use in machinery (3%) and electricity (2%).

In the Rotational Grazing scenario, emission from the cattle has decreased very modestly, representing 51% of the emissions. Grass silage rises to 21%, compound feed to 6%, while grass through rotational grazing contributes 20%. Diesel and electricity remain minor contributors at 1% and 2%, respectively.

The Cover Cropping scenario also shows a similar profile. The contribution from cattle is 62%, ryegrass-clover production accounts for second majority of the emissions, which is mainly due to the use of fertilizers and the emissions from the other categories are similar to the emissions in other scenarios.

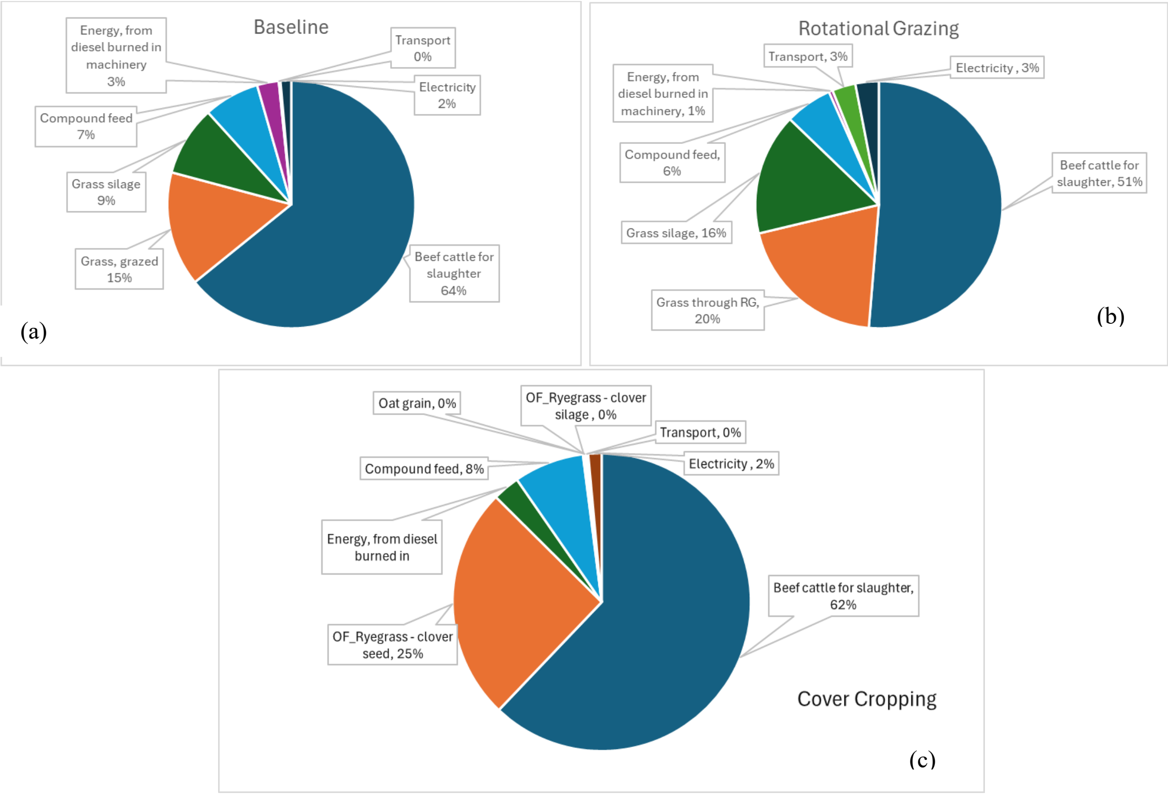

Figure 6: Distribution of Emissions across different categories a) Baseline b) RG c) CC

Every component of these systems contributes to emissions across four categories as defined by the IPCC GWP 100 method, which are the same as the emission contribution categories presented in Figure 6. It is to be noted that emissions from manure management are not explicitly represented as a separate category within the IPCC GWP 100 framework. Due to the absence of detailed data on manure storage and handling and emissions are included based on existing model built on assumptions from IPCC, manure management emissions are included within the biogenic category.

Transport of compound feed in this study is limited to domestic movements within Ireland, while electricity use is primarily associated with machinery operation and stable management. Similarly, diesel combustion represents energy use directly linked to field machinery operations. As these components account for only minor contributions to the overall GHG emission profile and are not directly attributable to land use change processes, their influence on the comparative outcomes is negligible. So they are excluded from further detailed analysis in subsequent sections and emissions from other components are further taken for analysis.

4.1 Biogenic emissions

The Biogenic Emissions impact category quantifies emissions originating from biological sources which are basically CH_4, direct & Indirect N_2O emissions from cattle through enteric fermentation and manure along with the decomposition of plant and animal material.

From the graph, it is evident that the “Beef cattle for slaughter” activity is the major contributor to biogenic emissions in all scenarios. The emissions remain relatively consistent between the Baseline and RG scenario, with a slight reduction under CC scenario. This indicates that changes in land management practices have only limited impact on emissions primarily driven by enteric fermentation.

The “Grass, grazed” activity shows emissions only under the Rotational Grazing scenario, reflecting additional CH_4 and N_2O emissions that is linked to grazing intensity and manure deposition on pasture. No emissions are observed for other feed components such as Grass silage, Compound feed, Ryegrass-clover seed, Ryegrass-clover silage, and Oat grain within the system boundary, indicating their negligible contribution to biogenic emissions in this assessment.

Overall, the results highlight that most biogenic emissions arise from cattle related activities rather than crop or feed production processes. Therefore, mitigation efforts should focus on improving enteric fermentation efficiency and manure management rather than crop related inputs to achieve significant emission reductions.

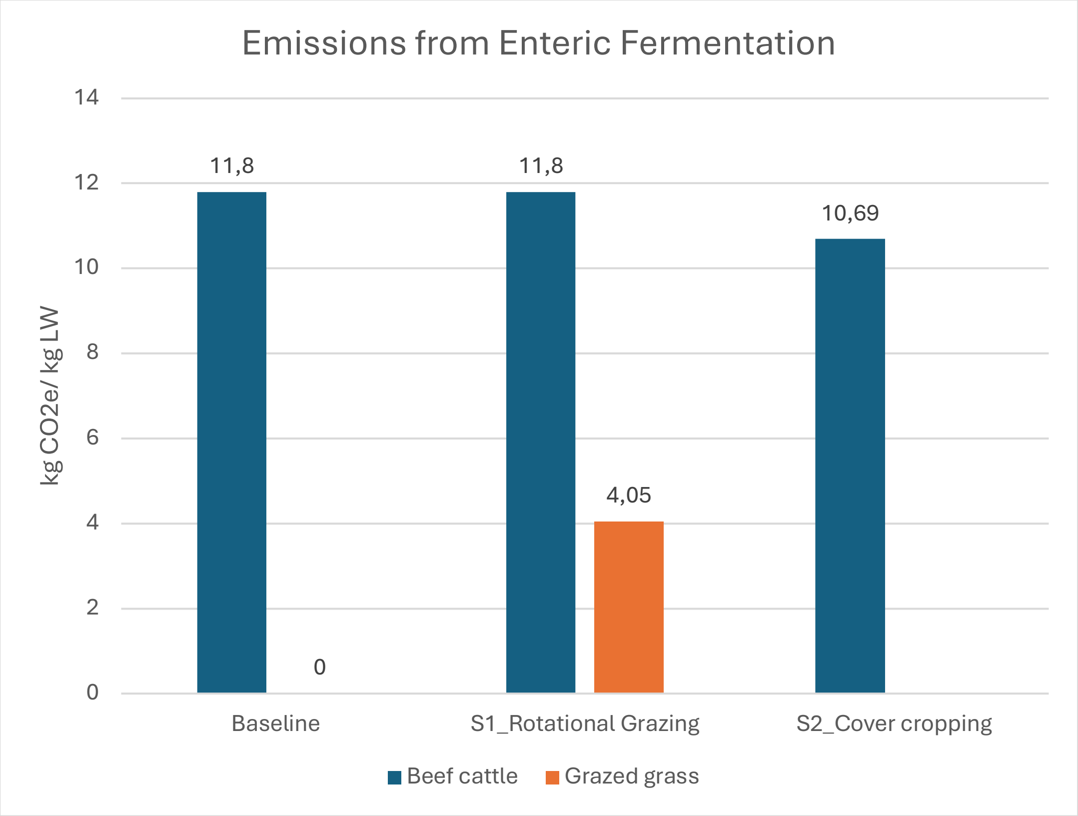

Figure 7: Biogenic Emissions representing all 3 scenarios

4.2 Emissions from fossil fuel

This graph presents the emissions from fossil fuels, which are GHG released from the activities that are involved. This impact category quantifies CO_2 emissions originating from fossil fuel combustion used in farm operations such as machinery, transport, and energy inputs for feed production and processing.

The “Grass, grazed” activity shows the highest fossil fuel emissions in the Baseline scenario which significantly decline under Rotational Grazing reflecting the lesser dependence on mechanical operations such as mowing, baling, and transporting feed when animals graze directly on pasture, thereby decreasing fuel and energy consumption.

For “Grass silage” and “Compound feed”, emissions remain consistent across all scenarios. This shows that these processes require similar energy inputs regardless of the land management practice applied. The “Ryegrass-clover seed” activity under the Cover Cropping scenario shows a spike, representing the most fossil-fuel-intensive process. This elevated value is due to the energy demanding seed production activities, including seed drying, processing, and transportation. The “Ryegrass-clover silage” and “Oat grain” activities contribute minimally to fossil fuel emissions, indicating the minor energy input requirements and exclusion from energy intensive processing stages.

This result emphasize that feed production and field operations are the dominant sources of fossil fuel-related emissions, while grazing management strategies can reduce fossil fuel dependency and associated CO_2 emissions at the farm level. The analysis from this impact category shows the direct energy footprint of each farm activity, showing where the production system relies on fossil fuels.

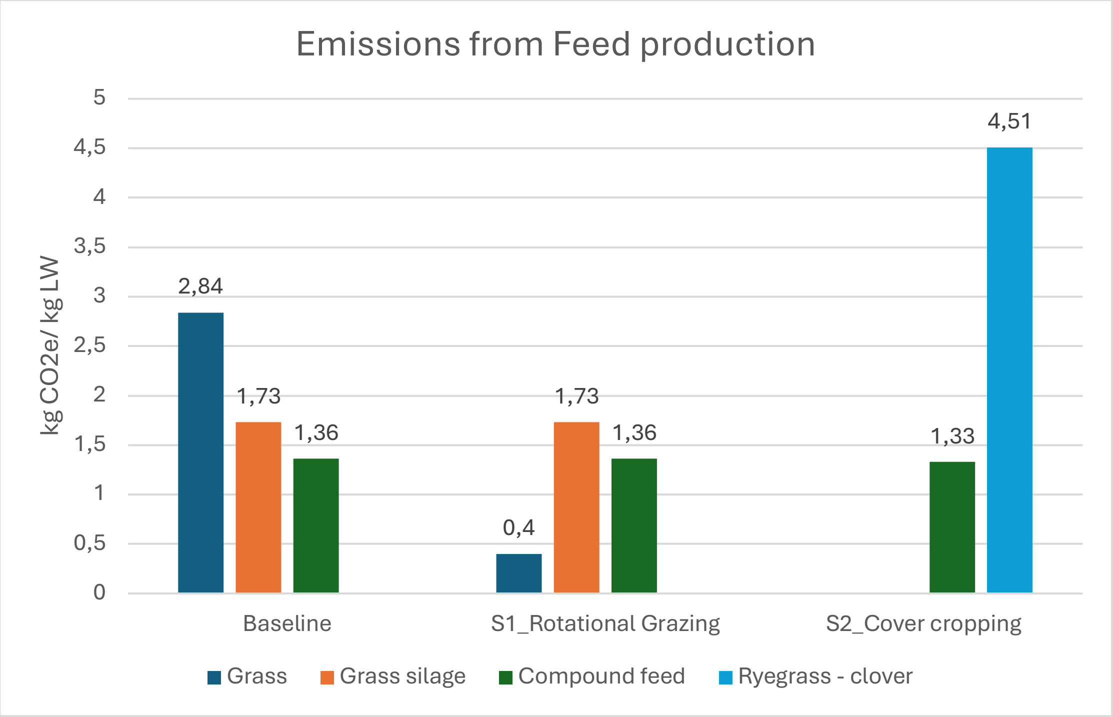

Figure 8 : Fossil fuels Emissions

4.3 Emissions from Land Transformation

This graph shows emissions caused by land transformation. The GHG emissions shown here doesn’t necessarily repeat the same pattern as they do in other impact category like emissions from fossil fuel or biogenic emissions. They are a one-time result of that happens when land use changes. A value in this category indicates that land was converted from grassland to cropland.

The results show that emissions from land transformation are only associated with the “Compound feed” category where there is land transformation for feed production in addition to the Ryegrass – clover in the CC scenario where pasture is converted to cropland. In contrast, the "Baseline" and "Rotational Grazing" scenarios have no emissions in this category, indicating that no land-use changes were assumed for these systems as they remain grasslands.

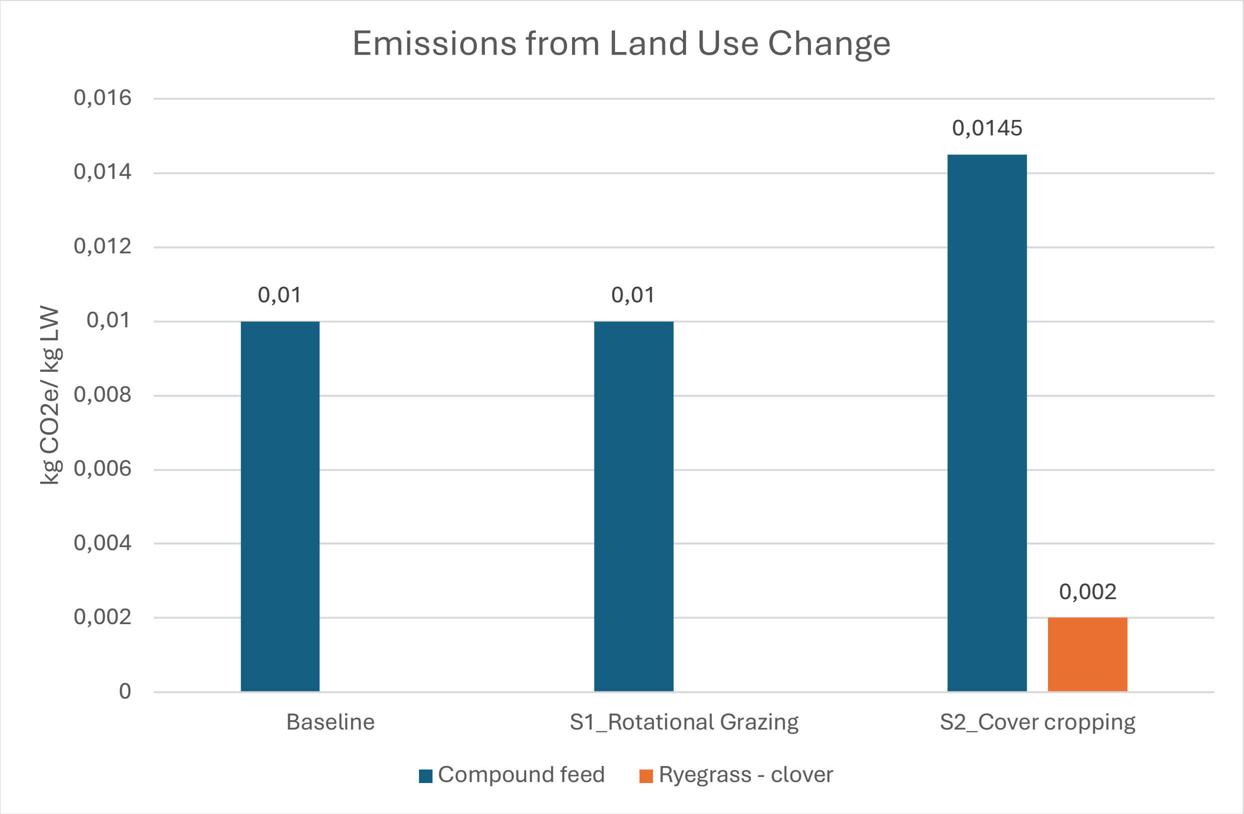

Figure 9: Land Transformation Emissions representing all 3 scenarios

4.4 Carbon removals

According to the GHG Protocol, carbon can be stored in two main forms, biogenic and technological. While technological storage refers to technical solutions such as carbon capture and storage (CCS) in geological formations, biogenic storage occurs naturally within ecosystems. Since this study focuses on agricultural practices, the primary form of carbon storage considered is biogenic. Biogenic carbon removal takes place through the uptake of atmospheric CO_2 by plants via photosynthesis and subsequently storing the carbon in different pools, mainly as soil Organic Carbon (SOC), biomass (Above &

Below ground), and Dead Organic matter. These pools serve as temporary or long-term reservoirs of carbon, eventually helping to offset the GHG emissions.

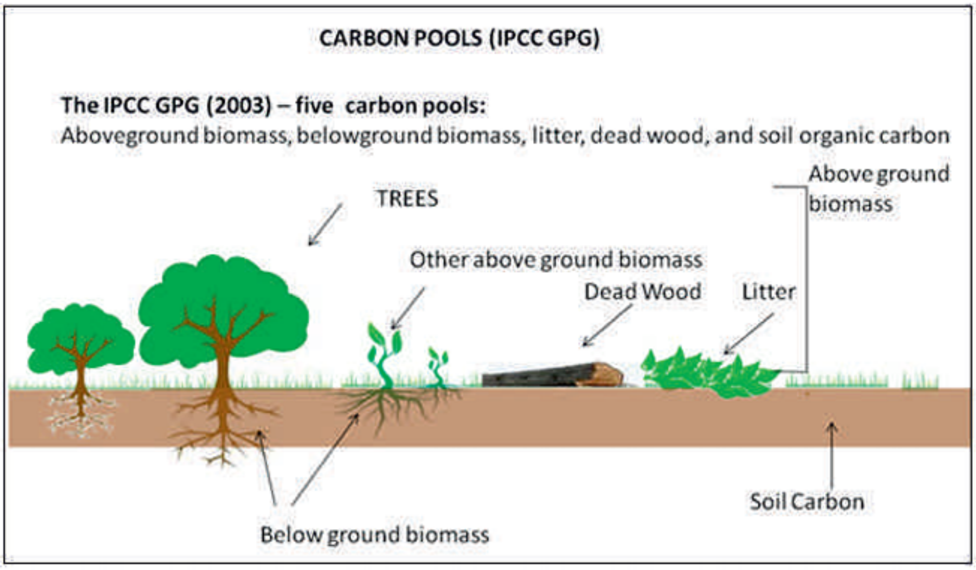

Figure 8.1: Carbon Pools (IPCC GPG)

Figure 10 below illustrates the key biogenic carbon pools according to IPCC.

- Above-ground biomass refers to all living plant material above the soil, such as leaves, stems, and trunks.
- Below-ground biomass refers to all living roots of trees and plants.
- Dead organic matter includes both dead wood and litter.
- Soil Organic Carbon (SOC) refers to the most important carbon pool in agricultural systems, SOC consists of decomposed plant and animal residues, microbial biomass, and humus.

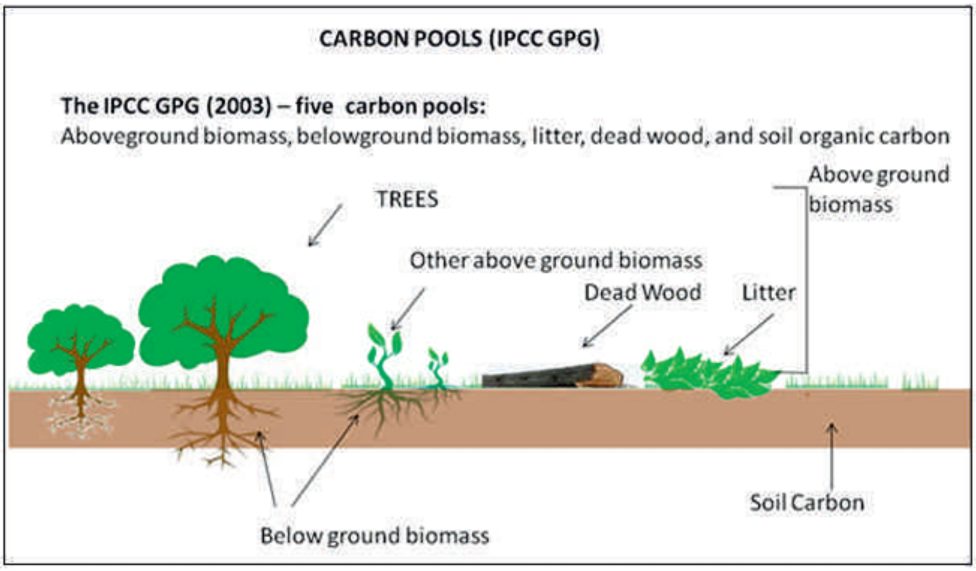

Figure 8.1: Carbon Pools (IPCC GPG)

Figure 10: Different Carbon pools

(Karmakar et al., 2020)

From the findings of the literature review, it is evident that as rotational grazing and cover cropping are highly effective strategies for biogenic carbon sequestration. These LMPs contribute significantly to carbon removal by actively increasing carbon stocks across the various biogenic pools. Carbon removals are measured by accounting for the carbon stocks across these pools. Cover cropping have been shown to contribute to three key carbon pools above-ground biomass, below-ground biomass, soil organic carbon (SOC), and dead organic matter and Rotational grazing contributes to the soil organic carbon stocks, based on the specific practices implemented.

The most common approach to quantify carbon stock changes is through direct field measurements, which provide site specific data. However, in this study, conducting field experiments or collecting data directly from the field was not feasible due to time and resource constraints. Therefore, methods mentioned in IPCC Guidelines were used to estimate carbon stock changes.

IPCC provides guidelines to account for carbon estimates categorized to 3 methods, i.e, Tier 1, 2 & 3. Tier 1 is the basic method, relying on basic data and default emission factors provided by the IPCC. This approach is best suited for countries or sectors with no to limited data. This method does not account for country-specific variables like climate, soil type, or management practices. As a result, Tier 1 estimates often have higher uncertainties. They provide a starting point to ensure a consistent accounting format globally, they may not accurately reflect the actual value of a specific region. Tier 2 is an intermediate approach that improves upon Tier 1 by incorporating country/region specific data. While the methodology remains the same as Tier 1, the emission factors and other parameters are obtained from databases available to the specific region. The estimate from this method is more accurate than Tier 1 because it reflects the characteristics of a particular region. The uncertainties are reduced in this tier providing a more reliable account of the carbon stocks. Tier 3 represents the most rigorous and accurate method for emissions accounting. It involves the use of complex, sophisticated models and site-specific data to track carbon stock changes over time. This method uses wide range of variables and their interactions, providing a detailed and highly reliable estimate. However, it is also the most resource-intensive, requiring extensive data collection, computational power, and expert knowledge to build and run the models.

Since data availability has been a challenge in this study, tier 1 method is used to account the estimates. Therefore, the factors used are default values from IPCC. Refer to ***Appendix – IV*** for detailed calculation methods, data sources, and assumptions used in the estimations.

The potential for carbon sequestration from SOC was quantified using IPCC default factors tailored for sustainably managed grasslands. This calculation assumes a minimum of one management improvement and moderate grazing pressure, starting from an initial non-degraded state. Under these specified conditions, and based on a representative grass yield of 36,300 kg/ha, the estimated Soil Organic Carbon is 0,087 kg/C/yr per kg LW. In a similar pattern, considering the CC scenario, ryegrass-clover would sequester SOC of 0,272 kg/C/yr per kg LW.

Table 4 : Summary of Carbon sequestration

Description	Carbon stocks (kg/C/yr per kg LW)	
	Grass	Ryegrass – Clover
Soil Organic Carbon	0,087	0,272

Among the different factors used to account the Soil Organic carbon, the primary reference value, SOC_{Ref} demonstrates a relatively high level of precision with an uncertainty of ± 5 %. The management factor (F_{MG}) presents the highest degree of variability among the quantified elements at ± 11 %, suggesting it is a significant contributor to the overall margin of error in the model. Finally, the input factor (F_I) shows a moderate uncertainty level of ± 7 %. Taken together, these figures highlight that management practices (F_{MG}) represent the most volatile variable in this analysis, requiring the most careful calibration for accurate results. Beyond these statistical uncertainties, SOC estimations represent a single point in time. Soil carbon storage is not permanent; soils have a finite capacity and eventually reach an equilibrium state. Further , sequestered carbon can be released again into the atmosphere due to changes in Land Management Practices (LMPs) or climate-induced ecosystem shifts.

Consequently, these estimations which rely on Tier 1 default factors should be interpreted with caution. The combination of measurement uncertainty and the reversible nature of soil sequestration means these figures serve as a preliminary guide rather than a definitive measure of long-term carbon removal. The drastic variations in removal rates in the literature underscore the necessity of moving beyond Tier 1 defaults toward site-specific modeling.

5 Discussion

This chapter is dedicated to the discussion of the research questions posed in Chapter 1, integrating the methodologies and findings derived from the Life Cycle Assessment (LCA) model developed in this thesis. The core of this discussion centers on comparing the implemented Land Management Practice (LMP) results to the existing evidence base presented in the literature review, thereby contextualizing the observed differences and validating the modeling approach. Furthermore, this section critically analyzes how the effectiveness of the different LMPs directly addresses the specific requirements set forth by the Science Based Targets initiative (SBTi) FLAG guidance to aggressively reduce emissions while successfully enhancing carbon removals in the beef production system.

The fundamental outcome from the literature is that LMPs like Rotational Grazing and Cover cropping when combined with different levels of tillage can reduce the carbon footprint of beef production. Studies by Dick et al. (2015) and Lupo et al. (2013) showed substantial GHG reductions, up to 57% and 24% respectively when replacing conventional or native pastures with improved managed systems. However, the drastic reductions shown in literatures when improved legume Pastures are used as cover crops (Dick et al., 2015) is due to the significant involvement of biomass integration. Agrosilvopastoral systems (Torres et al., 2017 & Monteiro et al., 2024) show up to 96% reduction or even net-negative emissions due to the carbon sequestration in these studies varying from 40-60 MgCO2eq/ha, most of which came from the aboveground biomass especially from trees. This shows that increasing the biomass per hectare could be one of the drivers in increasing carbon sequestration.

While the directional trend of emission reduction of the case study aligns with the literature review, the magnitude of GHG reduction observed in this study is significantly less aggressive than the average field-based reductions documented in the literature for the chosen LMPs.

Table 5 : Comparison of emission ranges (Literature Vs Current study)

Practice	Literature Range (Average Reduction)	Current Study
Rotational Grazing	15–57% reduction.	Reduction of 13% from Baseline
Cover Cropping	Highly variable, often resulting in significant reduction (40–60%)	Reduction of 7% from Baseline

In the results showed in Fossil Fuel and Biogenic Emissions charts (Fig xx), the Rotational Grazing scenario shows emissions nearly identical to Baseline. This is a critical misalignment from literature, where Rotational Grazing is consistently shown to be a high-impact strategy. Similarly, the Cover Cropping scenario in this analysis shows a marked increase in emissions from both Fossil Fuels and Biogenic sources. This is in stark contrast to studies like Da Silva et al. (2025), which showed up to 100% reductions.

Similarly, carbon removals calculated through IPCC shows very minimal sequestration compared to the values from literature. Therefore, this study does not fully capture the carbon storage potential from long term biomass accumulation, soil organic Carbon. The limited temporal scope, default factors and exclusion of aboveground biomass contributions further constrain the sequestration estimates. Consequently, while the results confirm the positive direction of impact from improved LMPs, they highlight the need for site-specific data, dynamic modeling approaches, and inclusion of aboveground biomass pools to more accurately represent the true mitigation potential of LMPs in beef production systems.

Synergistic approach refers to combining two or more LMPs that achieves a mitigation benefit greater than the sum of their individual benefits. The practices are combined together based on different goals. The performance of a regenerative farming including these LMPs hinges on the managed interaction between crops and animals. Plants and animals can support and strengthen the agroecosystem processes by acting combined, which is referred to as coupling in Peterson et al. (2020). This combination is necessary to significantly boost the farm's natural ecological functions, including carbon storage and water retention and several other benefits. The results from literature review also shows that when different practices like cover cropping & reduced tillage or cover cropping combined with RG, the outcomes often demonstrate amplified environmental benefits compared to when these practices are implemented independently. The synergistic approach of combining LMPs represents a transformative pathway forward in producing low-carbon beef production. Rather than focusing on isolated mitigation strategies, integrating complementary practices boosts the carbon sequestration, reduces emissions, and strengthens the functions of agroecosystems. Therefore, fostering synergy among LMPs could be considered one of the critical strategies to achieve sustainable livestock systems.

6 Limitations and uncertainties

One of the critical limitations of this study lies in the availability and quality of data. The analysis relies mainly on secondary, model-based parameters from databases developed in recent years. As a result, the estimated GHG values, may not fully represent current field conditions and could change with more recent, real-time measurements even though they are based on established models. This is often an acknowledged challenge in agricultural research. This limitation is not only due to data gaps but also the difficulty of collection and interpretation of information from different sources. The use of multiple databases makes it hard to connect results to specific regions, maintain consistent time trends, or compare findings across scales. Collecting detailed primary data for all stages of production would require significant time and resources. Although there were assumptions made and simulation is done with secondary data in this case, these may not fully reflect the complex realities of the studied systems.

Land based solutions also come with a significant opportunity cost. Grass based production systems require increased land use compared to conventional systems and this increased land footprint can put pressure on natural ecosystems and lead to additional emissions that could negate the benefits of sequestration. Also, focus on land management alone can sometimes worsen the enteric emissions problem. Some analyses suggest that grass fed cattle, due to their diet and longer finishing times, may emit more methane per kg of cattle than cattle raised in feedlots. (Stanley et al 2018). Therefore, a comprehensive and effective approach must integrate a mixed approach of solutions from improved feeding and manure management to more efficient breeding and strategic land management to address this multifaceted nature of beef's carbon footprint.

Another critical challenge in this study is the linear approach to reduce emissions or increase removals in agricultural systems. A linear, reductionist approach is well-suited for manufactured products which are made in a controlled, predictable process. However, Agricultural production is an inherently complex, dynamic system characterized by a wide array of products, regional and temporal variations, and diffuse, nonpoint emission sources that are difficult to attribute to a single crop or activity which leads to a number of major methodological flaws in applying a linear, input-output analysis to agriculture, particularly within the framework of a Life Cycle Assessment (LCA). Especially when it comes to the key problem of co-product allocation. A single agricultural system often yields multiple products, such as meat, milk, and manure for fertilizer from a dairy herd, or wool, meat, and grain from farming system. Allocating the environmental burdens of production to these various outputs is a complex and often subjective process. The choice of allocation can drastically alter the results, rendering direct comparisons between studies unreliable.

The method of assessment for the LCA used in this study is the IPCC GWP 100. This method applies a static, long-term metric to assess a dynamic, short-lived gas like methane (Allen et al., 2016). CO_2 persists in the atmosphere for centuries, whereas methane is a short-lived gas with an atmospheric life of only about 12 years and it is an incredibly potent warmer around 80 times in the first 20 years (Mar et al., 2022). By considering this intense warming capacity of methane over a 100-year time period, GWP 100 dilutes its severity, underestimating the initial warming pulse by a factor of 4 to 5 over the first 20 years (IPCC, Change (2023b)).

7 Recommendations for IKEA

To strengthen IKEA's future work on FLAG emissions and removals, it is first essential to transition from short term data and modeling assumptions toward long term field trials. Establishing longitudinal, farm level monitoring will provide the reliable, site-specific evidence necessary to verify how various land management practices (LMPs) perform under real world conditions over time. This foundational data should be supported by the adoption of improved modeling tools capable of capturing the non-linear nature of biogenic carbon dynamics. Because carbon sequestration and soil processes do not follow a linear path, integrating advanced biogenic models into existing frameworks like SimaPro or GWP accounting systems will significantly increase the accuracy of reported climate impacts.

Beyond data collection, it is recommended to IKEA to pursue a strategy of complementary mitigation measures to address emissions that land management alone cannot reach. Specifically, pairing LMPs with interventions such as feed additives is necessary to directly mitigate enteric methane, as land-based practices have limited influence on Enteric fermentation processes. The efficiency of these measures can be further enhanced by integrating Precision Livestock Farming (PLF) technologies. Utilizing real time data from sensors, drones, and automated systems would simultaneously improve the quality of GHG accounting and the operational efficiency of the farms themselves.

Furthermore, exploring alternative climate metrics, such as GWP20 or GWP*, would offer a more comprehensive perspective on methane's atmospheric behavior and its impact on near term warming.

However, these technical advancements must be grounded in an understanding of economic and social feasibility. Farmers often face significant barriers to adoption, including high costs, increased labor, and lack of specialized knowledge. For LMPs to be successfully scaled across diverse sourcing regions, it is critical to identify financially viable strategies and incorporate farmer perspectives, ensuring that sustainability goals align with the practical realities of global agriculture.

8 Conclusion and Future Research

This thesis shows that strategic land management can reduce GHG emissions in beef production while increasing carbon sequestration. The LCA case study of Irish beef systems revealed that rotational grazing, cover cropping, and agroforestry each make strong contributions. Rotational grazing improves forage regrowth and soil health was found to lower net GHG intensity, consistent with findings from literatures where Adaptive multi-paddock grazing methods turned beef finishing into a carbon sink. Cover cropping in forage rotations enhanced soil organic carbon and cut fertilizer emission, contributing substantial on-farm removals. Agroforestry shows high amount of carbon removals by adding tree biomass and litter inputs that could even offset emissions up to 100%.

The implications extend beyond Ireland. Beef production is increasingly scrutinized worldwide for its climate impact, yet this study illustrates how temperate, grass-fed systems can form to be part of the solution. By adopting synergistic LMPs, beef systems can move toward net-zero and even net-negative operational footprints. This dual pathway of reducing emissions and simultaneously increasing the removals fits the science-based FLAG mitigation framework, which envisions a rough 50/50 split of cuts and sinks (SBTi,n.d)

However, the implementation of these practices for the environmental benefits comes with limitations. The model did not include dynamic soil carbon by and our estimations of SOC changes was based on limited emission factors from IPCC. Soil carbon fluxes are highly site specific, so our estimated sequestration potentials cannot be simply scaled. Furthermore, this analysis focused static farm metrics based on data available from literature without accounting for dynamic changes in the process and other sustainability dimensions like economic and social aspects. Even if fully implemented, LMPs alone may not be able to achieve absolute net-zero as noted in the literature with continued growth in beef demand which is a whole another debate.

Future research could address these limitations and build on the findings from this study. Longer term, empirical field trials of rotational grazing, cover crop rotations, and silvopasture in temperate beef systems would refine SOC and GHG estimates. Integrating these management practices into farm economic and life cycle models would help assess tradeoffs and viability. Socio economic studies can also explore the ways in which regional farmers could adopt these pathways and provide incentives as part of policies for implementing multiple LMPs. Importantly, comparative studies across different regions would also explain clarify how context alters the effectiveness of LMPs. Research could also be extended to studying systems that integrate precision farming technologies which can considerably help in monitoring the systems and reduce uncertainties in emission estimation and management performances. This could also help in improving data accuracy, scaling sustainable practices.

Research into complementary measures like including improved feed rations, adding inhibitors or additives to reduce methane productions alongside land-based practices would identify comprehensive pathways to reduce emissions. Studying the synergy in details and how multiple practices combine to exceed individual benefits remains a key challenge for agronomic and modeling studies. Further research is critically required to accurately quantify and model the synergistic effects of combining multiple LMPs. Developing robust database and refining modelling frameworks to capture the non-linear ecological feedback loops remains challenge, but it is essential to advance in the long-term mitigation and carbon sequestration potential in integrated farming systems.

In conclusion, this thesis provides evidence that beef production need not be inherently climate intensive. By implementing well managed LMPs, beef systems can dramatically reduce their GHG footprint and actively draw down atmospheric carbon. Such multifunctional farming practices offer a climate friendly route for the FLAG sector by aligning agricultural productivity with climate targets and demonstrate that sustainable beef is achievable. Achieving these gains at scale will require continued innovation, supportive policy, and global commitment to integrate emission cutting and carbon removal solutions in agriculture.

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Appendix – I

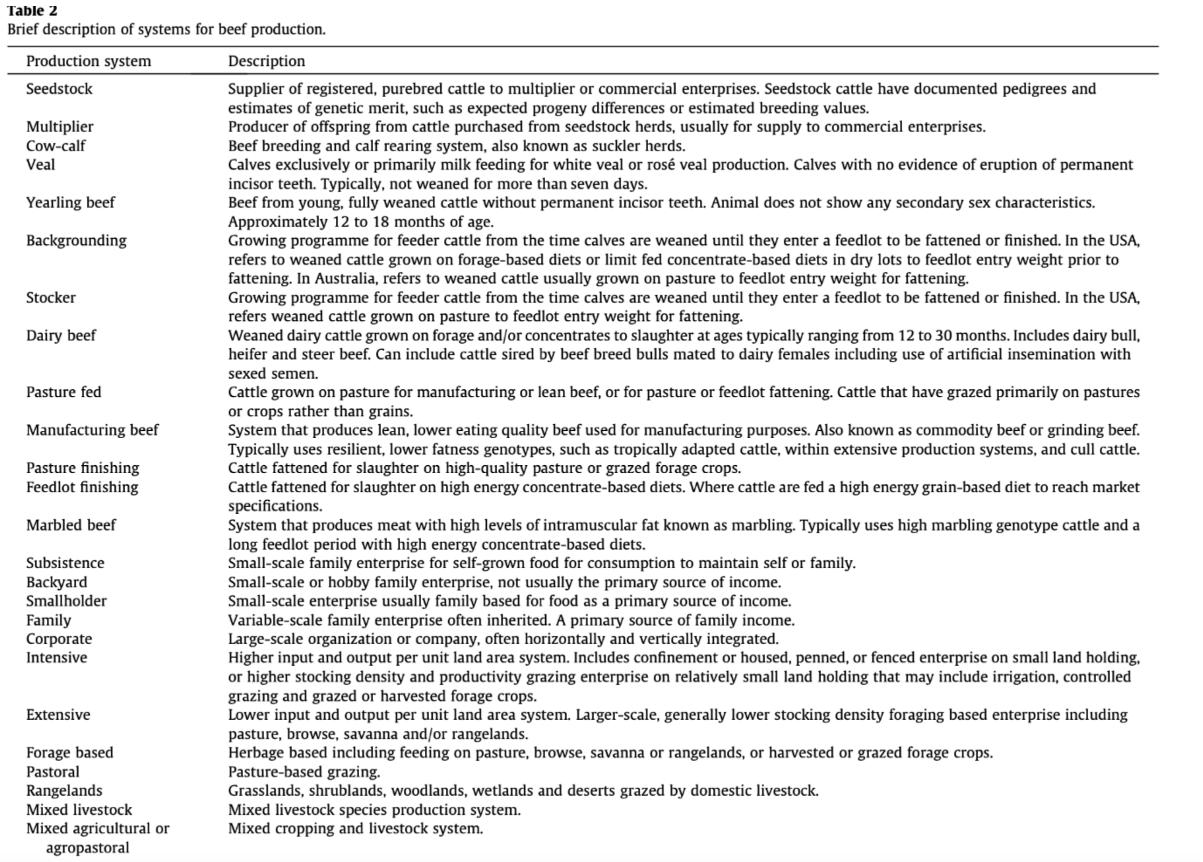


Table 2
Brief description of systems for beef production.

Production system	Description
Seedstock	Supplier of registered, purebred cattle to multiplier or commercial enterprises. Seedstock cattle have documented pedigrees and estimates of genetic merit, such as expected progeny differences or estimated breeding values.
Multiplier	Producer of offspring from cattle purchased from seedstock herds, usually for supply to commercial enterprises.
Cow-calf	Beef breeding and calf rearing system, also known as suckler herds.
Veal	Calves exclusively or primarily milk feeding for white veal or rosé veal production. Calves with no evidence of eruption of permanent incisor teeth. Typically, not weaned for more than seven days.
Yearling beef	Beef from young, fully weaned cattle without permanent incisor teeth. Animal does not show any secondary sex characteristics. Approximately 12 to 18 months of age.
Backgrounding	Growing programme for feeder cattle from the time calves are weaned until they enter a feedlot to be fattened or finished. In the USA, refers to weaned cattle grown on forage-based diets or limit fed concentrate-based diets in dry lots to feedlot entry weight prior to fattening. In Australia, refers to weaned cattle usually grown on pasture to feedlot entry weight for fattening.
Stocker	Growing programme for feeder cattle from the time calves are weaned until they enter a feedlot to be fattened or finished. In the USA, refers weaned cattle grown on pasture to feedlot entry weight for fattening.
Dairy beef	Weaned dairy cattle grown on forage and/or concentrates to slaughter at ages typically ranging from 12 to 30 months. Includes dairy bull, heifer and steer beef. Can include cattle sired by beef breed bulls mated to dairy females including use of artificial insemination with sexed semen.
Pasture fed	Cattle grown on pasture for manufacturing or lean beef, or for pasture or feedlot fattening. Cattle that have grazed primarily on pastures or crops rather than grains.
Manufacturing beef	System that produces lean, lower eating quality beef used for manufacturing purposes. Also known as commodity beef or grinding beef. Typically uses resilient, lower fatness genotypes, such as tropically adapted cattle, within extensive production systems, and cull cattle.
Pasture finishing	Cattle fattened for slaughter on high-quality pasture or grazed forage crops.
Feedlot finishing	Cattle fattened for slaughter on high energy concentrate-based diets. Where cattle are fed a high energy grain-based diet to reach market specifications.
Marbled beef	System that produces meat with high levels of intramuscular fat known as marbling. Typically uses high marbling genotype cattle and a long feedlot period with high energy concentrate-based diets.
Subsistence	Small-scale family enterprise for self-grown food for consumption to maintain self or family.
Backyard	Small-scale or hobby family enterprise, not usually the primary source of income.
Smallholder	Small-scale enterprise usually family based for food as a primary source of income.
Family	Variable-scale family enterprise often inherited. A primary source of family income.
Corporate	Large-scale organization or company, often horizontally and vertically integrated.
Intensive	Higher input and output per unit land area system. Includes confinement or housed, penned, or fenced enterprise on small land holding, or higher stocking density and productivity grazing enterprise on relatively small land holding that may include irrigation, controlled grazing and grazed or harvested forage crops.
Extensive	Lower input and output per unit land area system. Larger-scale, generally lower stocking density foraging based enterprise including pasture, browse, savanna and/or rangelands.
Forage based	Herbage based including feeding on pasture, browse, savanna or rangelands, or harvested or grazed forage crops.
Pastoral	Pasture-based grazing.
Rangelands	Grasslands, shrublands, woodlands, wetlands and deserts grazed by domestic livestock.
Mixed livestock	Mixed livestock species production system.
Mixed agricultural or agropastoral	Mixed cropping and livestock system.

Greenwood (2021b)

Appendix – II

Table 6 : Summary of Land Management practices in beef production systems

Beef production process	Land use/ Land Management practice	Description	Reference
Feed production (Pasture/Grazing establishment)	Organic grass-based systems integrated with mixed swards & Legumes	These systems basically rely use no fertilizers and pesticides, rely on animal manure for the nutrient requirement and get their nitrogen fixation from swards/clovers,etc.	O'Brien et al., 2023
	Agroforestry Integration	Combines trees with crops and/or livestock to create more diverse, productive, and sustainable land-use systems.But Agroforestry systems are further classified into 3 major types	Nair, P.K.R. (1993)
	Agrisilviculture	Combining agricultural crops with trees on the same land unit	Nair, P.K.R. (1993)
	Silvopastoral	integrate trees with pasture and livestock	Nair, P.K.R. (1993)
	Agrosilvopastoral	crops, trees, and livestock on the same land	Nair, P.K.R. (1993)
	Cover cropping	Grows specific crops to cover the soil	Pelletier et. al.,2010
	Crop Rotation	Alternates different crops in the same area	Pelletier et. al.,2010
	Reduced Tillage/No tillage	Managing Tillage to minimize soil disturbance	Pelletier et. al.,2010
	Compost Application	Applying decomposed organic matter soil	Papadopoulos et al. (2024)
	Precision Fertilizer application	Utilizes technology to apply fertilizers efficiently	Papadopoulos et al. (2024)

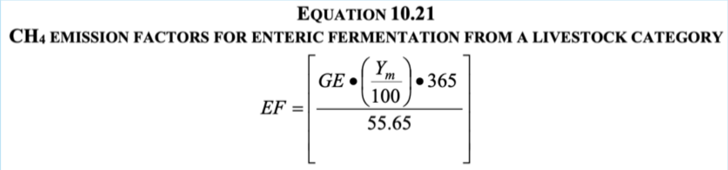
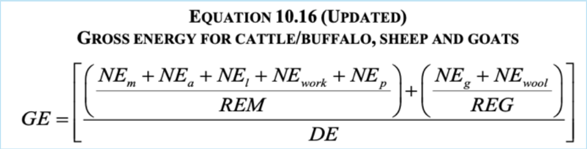
Beef production process	Land use/ Land Management practice	Description	Ref
Rearing & Growth	Rotational Grazing	Moves livestock between different pastures	Sheppard et al., 2016
- Grazing Management practices	Strip Grazing	Allocates narrow strips of pasture for grazing	Sheppard et al., 2016
	Adaptive Multi -paddock grazing	Adjusts grazing patterns based on forage availibility	Pelletier et al. (2010)
	Winter grazing	Utilizes stockpiled forage during winter months	Sheppard et al., 2016
Farm operations **- Manure Management Practices**	Manure storage & composting	Stores and d23ecomposes manure and produces compost	Wang et al., 2021
	Biofiltration	Uses biological systems to filter and treat manure	Lupo et al., 2013
	Direct injection	Injects manure directly into the soil	Lupo et al., 2013
	Improved Manure Management using controlled grazing corridors	Manages livestock movement to distribute manure evenly	Wang et al. (2021)
	Improved Manure Management using Designated water points	Establishes specific watering areas to prevent water contamination from manure	Chadwick et al. (2011)
Precision Livestock Farming	Automatic weighing Platforms	Monitors animal weight gain for efficient feeding	McNicol et al., 2024
	Health & Fertility sensors	Tracks vital signs and reproductive status	McNicol et al., 2024
	Precision Fertilizer application	Applies fertilizers using different equipments like drones/tractors based on real-time data	Polwaththa et al. (2024)

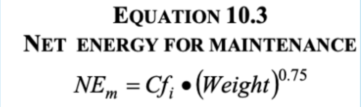
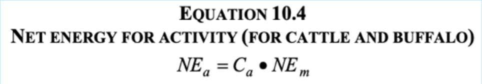
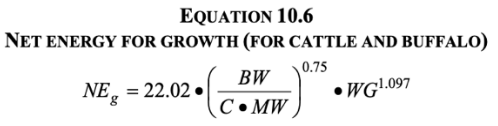
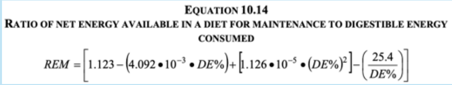
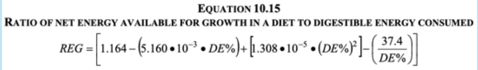
Appendix – III

CH_4 Emission Factor for Enteric Fermentation

(Equation numbers are maintained the same as IPCC for simplicity in reference)

Table 7 : Methane Emission due to Enteric fermentation

Symbol	Description	IPCC Equation/Reference	Unit	Value
EF	Methane Emission Factor For Enteric Fermentation From A Livestock Category	 EQUATION 10.21 CH_4 EMISSION FACTORS FOR ENTERIC FERMENTATION FROM A LIVESTOCK CATEGORY $EF = \left[\frac{GE \bullet \left(\frac{Y_m}{100} \right) \bullet 365}{55.65} \right]$	kg CH_4 head^{-1} yr^{-1}	232.88
Y_m	Methane conversion factor, per cent of gross energy in feed converted to methane	Table 10.12 of IPCC , Vol.4, Chapter 10	%	7.5
GE	Gross energy intake	 EQUATION 10.16 (UPDATED) GROSS ENERGY FOR CATTLE/BUFFALO, SHEEP AND GOATS $GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g + NE_{wool}}{REG} \right)}{DE} \right]$	MJ head^{-1} day^{-1}	473.41

Symbol	Description	IPCC Equation/Reference	Unit	Value
NE_m	Net Energy required by the animal for maintenance	 **EQUATION 10.3** **NET ENERGY FOR MAINTENANCE** $NE_m = Cf_i \bullet (Weight)^{0.75}$	MJ day^{-1}	41.31
Cf_i	Coefficient for calculating NE_m	Table 10.4 of IPCC , Vol.4, Chapter 10	MJ day^{-1} kg^{-1}	0.322
NE_a	Net Energy for animal activity	 **EQUATION 10.4** **NET ENERGY FOR ACTIVITY (FOR CATTLE AND BUFFALO)** $NE_a = C_a \bullet NE_m$	MJ day^{-1}	7.02
C_a	Coefficient corresponding to animal's feeding situation	Table 10.5 of IPCC , Vol.4, Chapter 10	MJ day^{-1} kg^{-1}	0.17
NE_{work}	Net energy for work	Considered as 0 as the cattle is not involved in any work and only calves and heifers are part of the herd		
NE_p	Net energy for pregnancy			
NE_g	Net Energy needed for Growth	 **EQUATION 10.6** **NET ENERGY FOR GROWTH (FOR CATTLE AND BUFFALO)** $NE_g = 22.02 \bullet \left(\frac{BW}{C \bullet MW}\right)^{0.75} \bullet WG^{1.097}$	MJ day^{-1}	37.78
BW	Average live body weight of the animals in the population		kg	650
MW	Mature live body weight of an adult animal in moderate body condition		kg	647
WG	Average daily weight gain	Pelletier et al. (2010)	Kg day^{-1}	1.4
C	Coefficient for calculating net energy for growth	IPCC , Vol.4, Chapter 10	-	0.8
REM	Ration of Net energy available in a diet for maintenance to digestible energy consumed	 **EQUATION 10.14** **RATIO OF NET ENERGY AVAILABLE IN A DIET FOR MAINTENANCE TO DIGESTIBLE ENERGY CONSUMED** $REM = \left[1.123 - \left(4.092 \bullet 10^{-3} \bullet DE\%\right) + \left[1.126 \bullet 10^{-5} \bullet (DE\%)^2\right] - \left(\frac{25.4}{DE\%}\right)\right]$	-	
REG	Ration of Net energy available in a diet to digestible energy consumed	 **EQUATION 10.15** **RATIO OF NET ENERGY AVAILABLE FOR GROWTH IN A DIET TO DIGESTIBLE ENERGY CONSUMED** $REG = \left[1.164 - \left(5.160 \bullet 10^{-3} \bullet DE\%\right) + \left[1.308 \bullet 10^{-5} \bullet (DE\%)^2\right] - \left(\frac{37.4}{DE\%}\right)\right]$	-	
DE	Digestible energy expressed as a % of gross energy	Dick et al. (2015)	%	55

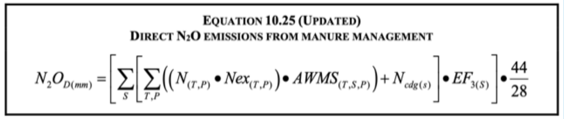
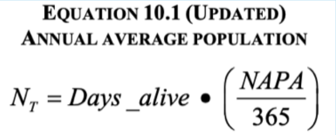
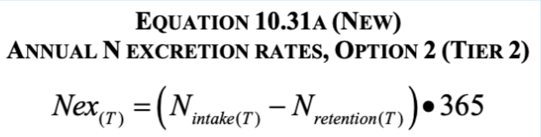
CH_4 Emission Factor for Manure Management

Table 8: Methane Emission due to Manure Management

Symbol	Description	IPCC Equation/Reference	Unit	Value		
EF	Methane Emission Factor from Manure management	EQUATION 10.23 CH_4 EMISSION FACTOR FROM MANURE MANAGEMENT[5] $EF_{(T)} = (VS_T \bullet 365)\left[B_{0(T)} \bullet 0.67 \bullet \sum_{S,k} \frac{MCF_{S,k}}{100} \bullet AWMS_{(T,S,k)}\right]$	kg CH_4 $head^{-1}$ yr^{-1}	24,51		
$VS_{(T)}$	Daily volatile solid excreted for livestock category T	EQUATION 10.24 (UPDATED) VOLATILE SOLID EXCRETION RATES $VS = \left[GE \bullet \left(1-\frac{DE}{100}\right) + (UE \bullet GE)\right] \bullet \left[\left(\frac{1-ASH}{18.45}\right)\right]$	kg VS day-1 head-1	11,49		
$B_{o(T)}$	Maximum methane producing capacity for manure produced by livestock category T	Table 10.16A of IPCC , Vol.4, Chapter 10	m3 CH4 kg-1	0.18		
$MCF_{(S,k)}$	Methane conversion factors for each manure management system *S* by climate region *k*, percent	Table 10.17 of IPCC , Vol.4, Chapter 10	%	Liquid/Slurry, and Pit storage below animal confinements	Pasture/ Paddock	Solid storage
				21	0.47	2

Symbol	**Description**	**IPCC Equation/Reference**	**Unit**	**Value**		
AWMS$_{(T,S,k)}$	Fraction of livestock category *T*'s manure handled using animal waste management system *S* in climate region *k*	Table 10 A.6 of IPCC , Vol.4, Chapter 10	-	Liquid/Slurry, and Pit storage below animal confinements	Pasture/ Paddock	Solid storage
				22	48	26
UE*GE	Urinary energy expressed as fraction of GE	Typically 0.04GE can be considered urinary energy excretion by most ruminants (IPCC , Vol.4, Chapter 10)	MJ day^{-1}	18.94		
ASH	The ash content of feed calculated as a fraction of the dry matter feed intake	https://www.feedtables.com/content/ash	-	0.086		

Table 9 : Direct N2O Emissions from Manure management

Symbol	Description	IPCC Equation/Reference	Unit	Value
$N_2O_{D(mm)}$	Direct N_2O emissions from Manure Management	 EQUATION 10.25 (UPDATED) DIRECT N_2O EMISSIONS FROM MANURE MANAGEMENT $N_2O_{D(mm)} = \left[\sum_S \left[\sum_{T,P} \left(\left(N_{(T,P)} \bullet Nex_{(T,P)} \right) \bullet AWMS_{(T,S,P)} \right) + N_{cdg(s)} \right] \bullet EF_{3(S)} \right] \bullet \frac{44}{28}$	kg N_2O yr^{-1}	14,81
$N_{(T,P)}$	Number of head of livestock species/category *T* in the country, for productivity system *P*, (,) *T P* when applicable	 EQUATION 10.1 (UPDATED) ANNUAL AVERAGE POPULATION $N_T = Days\_alive \bullet \left(\frac{NAPA}{365} \right)$		2
$N_{ex(T,P)}$	Annual average N excretion per head of species/category *T* in the country, for productivity system *P*, when applicable	 EQUATION 10.31A (NEW) ANNUAL N EXCRETION RATES, OPTION 2 (TIER 2) $Nex_{(T)} = \left(N_{intake(T)} - N_{retention(T)} \right) \bullet 365$	kg N $animal^{-1}$ yr^{-1}	234,86

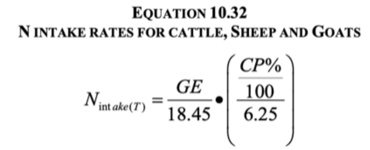
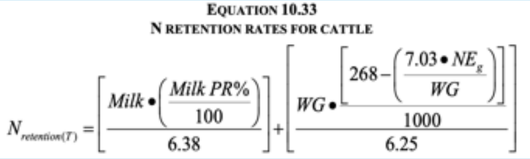
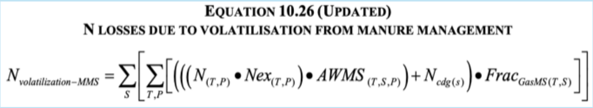
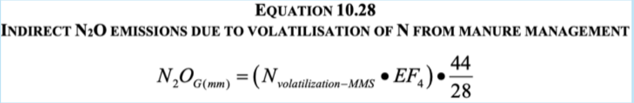
Symbol	Description	IPCC Equation/Reference	Unit	Value		
N_{intake}	Nitrogen intakes for cattle	 EQUATION 10.32 N INTAKE RATES FOR CATTLE, SHEEP AND GOATS $N_{intake(T)} = \frac{GE}{18.45} \bullet \left(\frac{\frac{CP\%}{100}}{6.25} \right)$	kg N $animal^{-1}$ day^{-1}	0.66		
$N_{retention}$	Daily N retained per animal	 EQUATION 10.33 N RETENTION RATES FOR CATTLE $N_{retention(T)} = \left[\frac{Milk \bullet \left(\frac{Milk\ PR\%}{100} \right)}{6.38} \right] + \left[\frac{WG \bullet \left[\frac{268 - \left(\frac{7.03 \bullet NE_g}{WG} \right)}{1000} \right]}{6.25} \right]$	kg N $animal^{-1}$ day^{-1}	0,0175		
$N_{cdg(s)}$	Annual nitrogen input via co-digestate in the country, where the system (s) refers exclusively to anaerobic digestion		kg N yr^{-1}	45		
$EF_{3(s)}$	Emission factor for direct N2O emissions from manure management system		kg N_2O-N/kg N	Liquid/Slurry, and Pit storage below animal confinements 0.005	Pasture/ Paddock 0.004	Solid storage 0.01

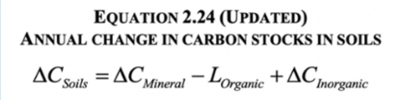
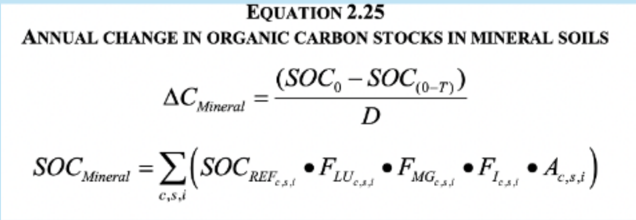
Table 10 : Indirect N2O Emissions from Manure management

Symbol	Description	IPCC Equation/Reference	Unit	Value		
$N_{volatilization-MMS}$	Indirect N_2O emissions from Manure Management	 EQUATION 10.26 (UPDATED) N LOSSES DUE TO VOLATILISATION FROM MANURE MANAGEMENT $N_{volatilization-MMS} = \sum_{S}\left[\sum_{T,P}\left[\left(\left(\left(N_{(T,P)} \bullet Nex_{(T,P)}\right) \bullet AWMS_{(T,S,P)}\right) + N_{cdg(s)}\right) \bullet Frac_{GasMS(T,S)}\right]\right]$	kg Nyr^{-1}	2.25		
$Frac_{GasMS(T,S)}$				Liquid/Slurry, and Pit storage below animal confinements 0.48	Pasture/ Paddock 0	Solid storage 0.45
$N_2O_{G(mm)}$	Indirect N2O emissions due to volatilization of N from Manure Management	*  EQUATION 10.28 INDIRECT N_2O EMISSIONS DUE TO VOLATILISATION OF N FROM MANURE MANAGEMENT $N_2O_{G(mm)} = \left(N_{volatilization-MMS} \bullet EF_4\right) \bullet \frac{44}{28}$	kg N_2O yr^{-1}	3.6		

Appendix – IV

Estimating Carbon Removals based on IPCC

Table 11 : Change in Soil Organic Carbon

Symbol	Description	IPCC Equation	Unit	Value
ΔC_{soils}	Annual change in carbon stocks in soils	 **EQUATION 2.24 (UPDATED)** **ANNUAL CHANGE IN CARBON STOCKS IN SOILS** $\Delta C_{Soils} = \Delta C_{Mineral} - L_{Organic} + \Delta C_{Inorganic}$	tonnes C yr^{-1}	-42,92
$L_{organic}$	Annual loss of carbon from drained organic soils, tonnes C yr-1	Emission factors to calculate Losses from Table 2.1 of IPCC , Vol.4, Chapter 2	tonnes C yr^{-1}	61.2
$\Delta C_{Inorganic}$	annual change in inorganic carbon stocks from soils, tonnes C yr-1 (assumed to be 0 unless using a Tier 3 approach)	-	-	0
$\Delta C_{mineral}$	annual change in organic carbon stocks in mineral soils	 **EQUATION 2.25** **ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS** $\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$ $SOC_{Mineral} = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$	tonnes C yr^{-1}	18,28

Symbol	Description	IPCC Equation	Unit	Value	
SOC_0	Mineral soil organic C stock (SOCMineral) in the last year of an inventory time period	Based on Eq.2.25	tonnes C	81	
SOC_{0-T}	Mineral soil organic C stock (SOCMineral) at the beginning of the inventory time period	Based on Eq.2.25	tonnes C	92,34	
D	Time dependence of mineral soil organic C stock change factors which is the default time period for transition between equilibrium SOC values, yr.	Commonly 20 years, but depends on assumptions made in computing the factors FLU, FMG and FI. If T exceeds D, use the value for T to obtain an annual rate of change over the inventory time period (0-T years)	years	20	
SOC_{REF}	The soil organic C stock for mineral soils in the reference condition	Table 2.3 of IPCC , Vol.4, Chapter 2	tonnes C ha-1	81±5%	
$F_{LUF\ c\ s\ i}$	Stock change factor for mineral soil organic C land-use systems or sub-systems for a particular land-use	Table 6.2 of IPCC , Vol.4, Chapter 6		Time 0 1	Time (0-T) 1
$F_{MG\ c\ s\ i}$	stock change factor for mineral soil organic C for management regime, dimensionless			Time 0 1	Time (0-T) 1.14
$F_{I\ c\ s\ i}$	"stock change factor for mineral soil organic C for the input of organic amendments, dimensionless"			Time 0 1	Time (0-T) 1.11

Appendix – V

The criteria for selecting the cover crops is based on Sharma et al. (2018) and Jannoyer et al. (2011) and the list of cover crops and their combinations recommendation is based on (Cover Crop Mixtures | AHDB, n.d.)

Each criterion mentioned is assigned a weight of 1-10 showing its importance. Each crop is scored from 1 to 5 based on their performance for the criteria. The final weighted scores are provided as = criterion weight x crop score. This is summed to give an overall total and the crops with highest scores are selected and combined to act as cover crops for this case.

Table 12 : Selection of cover crops based on MCDA

		Legumes					**Cereals/grass**			
weight (1-10)	**Criteria / Crops**	**Vetch**	**Clover (white)**	***Clover (red)***	**Alfalfa**	**Peas**	***Oats***	**Forage Radish**	***Ryegrass***	**Fescue**
3	Regrowth capacity	3	4	***3***	2	2	***2***	2	***5***	4
8	Nitrogen fixation ability	5	5	***5***	5	4	***1***	1	***1***	1
7	Biomass production	3	3	***4***	4	3	***5***	5	***4***	4
5	Growth speed	3	4	***3***	2	3	***5***	5	***4***	3
8	Carbon sequestration potential	4	4	***5***	4	3	***4***	4	***5***	5

10	Drought/cold tolerance	3	5	***4***	2	3	***5***	4	***5***	5
5	Growth in reduced tillage	3	4	***4***	3	3	***5***	4	***5***	5
3	Trampling tolerance	2	4	***3***	2	2	***3***	2	***5***	5
8	Data availability in Ecoinvent	2	5	***5***	5	5	***5***	2	***5***	2
8	Nutrition for Cattle (Protien/Digestibility)	3	4	***5***	5	4	***4***	2	***5***	5
	Overall Total score	208	279	***281***	237	221	***262***	204	***281***	249

Appendix – VI

Table 13: Life Cycle Inventory - Baseline

Beef Cattle					
Process	Agrifootprint category	Qty	Unit	Reference	Comments
Output					
Beef cattle	Beef cattle for slaughter at the farm (PEF Compliant), Irish	1	kg	Blonk et al. (2023)	
Inputs					
Water	Water from unspecified natural origin	0,0502	m^3	Blonk et al. (2023)	
Grass	Grass grazed in the pasture/IE mass	52,9	kg		
	Grass silage (beef), at farm/IE mass	10,4	kg		
Compound Feed (CF)	Compund feed Beef Cattle/IE mass	2,8	kg		
Energy	Energy from diesel burned in machinery/RER Mass	5,82	MJ		
Transport of CF to the farm	Transport, truck>20t, Euro4,80%LF,default/GLO Mass	0,644	tkm		
Electricity	Electricity mix, AC, Consumption mix,at consumer, < 1kV IE S System – copied from ELCD	0,304	kWh		
Emissions					
Methane from EF	Methane, Biogenic	0,36	kg	Blonk et al. (2023)	
Methane from MM	Methane, Biogenic	0,036	kg		
N_2O (Direct) from stable	Dinitrogen Monoxide	0,00122	kg		
N_2O (Indirect) from stable	Dinitrogen Monoxide	0,000192	kg		
	Particulates,< 10 um	0,4661	kg		
	Ammonia	0,038	kg		
	NMVOC,non-methane Volatile organic compounds	0,0112	kg		

Grass grazed in the pasture/IE mass				
Output		36300	kg	
Grass	Grass grazed in the pasture/IE mass			
Input				
Pasture Occupied	Occupation,grassland/Pasture/meadow	10000	m^2a	
Energy	Energy, from diesel burned in machinery/RER Mass	4268,2	MJ	
Fertilizer	Potassium chloride (NPK 0-0-60)	9,68	kg	
	Manure (cows), at farm	0,156	kg	
	NPK compound (NPK 15-15-15)	38,82	kg	
	PK compound (NPK 0-22-22)	1,52	kg	
	Di ammonium phosphate, as 100% (NH3)2HPO4 (NPK 22-57-0)	4,79	kg	
	Single superphosphate, as 35% Ca(H2PO4)2 (NPK 0-21-0)	0,531	kg	
	Ammonium sulfate, as 100% (NH4)2SO4 (NPK 21-0-0)	3,2	kg	Blonk et al. (2023)
	Calcium ammonium nitrate (CAN), (NPK 26.5-0-0)	127,81	kg	
	Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	25,28	kg	
	Lime fertilizer	400	kg	
Emissions to air, Water & Soil	Dinitrogen monoxide	0,597	kg	
	Dinitrogen monoxide	0,254	kg	
	Ammonia	9,23	kg	
	Ammonia	6,56	kg	
	CO2, Fossil	194,54	kg	
	Dinitrogen monoxide	1,55	kg	
	Dinitrogen monoxide	0,849	kg	
	Dinitrogen monoxide	0,349	kg	
	Dinitrogen monoxide	0,276	kg	
	CO2, Land transformation	0	kg	
	Nitrate	50,49	kg	
	Cadmium	18,49	mg	
	Chromium	12823,07	mg	
	Copper	1540,32	mg	Blonk et al. (2023)
	Mercury	0,158	mg	
	Nickel	0	mg	
	Lead	83,18	mg	
	Zinc	4252,5	mg	

	Nitrate	131,02	kg	
	Nitrate	71,74	kg	
	Phosphorous	0,65	kg	
	Cadmium	27,92	mg	
	Chromium	8009,72	mg	
	Copper	10188,71	mg	
	Mercury	6,09	mg	
	Nickel	1049,29	mg	
	Lead	80,52	mg	
	Zinc	18561,31	mg	
	Phosphorous	0,45	kg	
Grass silage (beef), at farm/IE Mass				
Output				
Grass silage	Grass silage (beef), at farm/IE Mass	0,34	kg	Blonk et al. (2023)
Inputs				
Grass	Grass, grazed in the pasture	1	kg	
Packing	Polyethylene low density granulate (PE-LD), production mix, at plant RER System - Copied from ELCD	0,00125	kg	Blonk et al. (2023)
Emissions				
	Water	0,66	kg	
Compound Feed				
Outputs				
Compound feed	Compound feed beef cattle/IE Mass	1	kg	
Inputs				
Barley	Barley grain, consumption mix	290	g	Blonk et al. (2023)
Wheat	Wheat grain, consumption mix	90	g	
Sugarcane	Sugar cane molasses, consumption mix	50	g	
Rapeseed	Rapeseed meal, consumption mix	150	g	
Oats	Oat grain, consumption mix	90	g	
Soybean	Soybean, consumption mix	120	g	
Maize	Maize, consumption mix	210	g	
Electricity	Electricity at consumer, < 1kV IE S System	0,293	MJ	

Heat	Heat, from residential heating systems from NG, at consumer, temperature of 55°C EU-27 S System	0,126	MJ		

Rotational Grazing

Table 14: Life Cycle Inventory – Rotational Grazing

Process	Agrifootprint category	Qty	Unit	Reference	Comments
Grass from Pasture through RG					
Inputs from technosphere					
Grass (Grazed Pasture)	MS2>Grass, grazed in Pasture/IE Mass	0.14	kg	Blonk et al. (2023)	
Grass (Resting Pasture)	MS2_Resting>Grass, grazed in Pasture/IE Mass	0.86	kg		
Grass (Grazed Pasture)					
Outputs to technosphere					
Grass (Grazed Pasture)	MS2>Grass, grazed in Pasture/IE Mass	8820900,00	kg		
Inputs					
Land occupied	Occupation,grassland/Pasture/Meadow	2430000,00	m²a	Blonk et al. (2023)	
Energy	Energy, from diesel burned in machinery/RER Mass	10371,726	MJ		
Manure	Manure (cows), at farm	0,37908	kg		
Fertilizer	Potassium chloride (NPK 0-0-60)	23,5224	kg		
	NPK compound (NPK 15-15-15)	94,3326	kg		
	PK compound (NPK 0-22-22)	3,6936	kg		
	Di ammonium phosphate, as 100% (NH3)2HPO4 (NPK 22-57-0)	11,6397	kg		
	Single superphosphate, as 35% Ca(H2PO4)2 (NPK 0-21-0)	1,29033	kg		
	Ammonium sulfate, as 100% (NH4)2SO4 (NPK 21-0-0)	7,776	kg		

	Calcium ammonium nitrate (CAN), (NPK 26.5-0-0)	310,5783	kg	Blonk et al. (2023)	
Emissions to air, Water & Soil	Urea, as 100% CO(NH2)2 (NPK 46.6-0-0)	61,4304	kg		
	Lime fertilizer	972	kg		
	Dinitrogen monoxide	1,45071	kg		
	Dinitrogen monoxide	0,61722	kg		
	Ammonia	22,4289	kg		
	Ammonia	15,9408	kg		
	CO2, Fossil	472,7322	kg		
	Dinitrogen monoxide	3,7665	kg		
	Dinitrogen monoxide	2,06307	kg		
	Dinitrogen monoxide	0,84807	kg		
	Dinitrogen monoxide	67,068	kg		
	CO2, Land transformation	0	kg		
	Nitrate	122,6907	kg		
	Cadmium	44,9307	mg		
	Chromium	31160,0601	mg		
	Copper	3742,9776	mg		
	Mercury	0,38394	mg		
	Nickel	0	mg		
	Lead	202,1274	mg		
	Zinc	10333,575	mg		
	Nitrate	318,3786	kg	Blonk et al. (2023)	
	Nitrate	174,3282	kg		
	Phosphorous	1,5795	kg		
	Cadmium	67,8456	mg		
	Chromium	194636,196	mg		
	Copper	24758,5653	mg		
	Mercury	14,7987	mg		

	Nickel	**2549,7747**	**mg**		
	Lead	195,6636	mg		
	Zinc	45103,9833	mg		
	Phosphorous	1,0935	kg		
Grass (Resting Pasture)					
Inputs					
Land occupied	Occupation,grassland/Pasture/Meadow	14570	m^{2}a		

Cover cropping

Table 15: Life Cycle Inventory – Crop Cropping

Process	Agrifootprint category	Qty	Unit	Reference	Comments
Beef Cattle					
Output					
Beef cattle	Beef cattle for slaughter at the farm (PEF Compliant), Irish	1	kg		
Inputs					
Water	Water from unspecified natural origin	0,0502	m^3		
Grass	OF_Ryegrass-clover seed, organic, at farm gate/FR U	51,425	kg	Blonk et al. (2023)	
	OF_Ryegrass-clover silage (beef) at farm/IE Mass	5,581	kg		
	Oat grain, at farm/IE mass	0,150			
Compound Feed (CF)	Compound feed Beef Cattle/IE mass	2,73	kg		

Process	Agrifootprint category	Qty	Unit	Reference	Comments
Energy	Energy from diesel burned in machinery/RER Mass	5,82	MJ		
Transport of CF to the farm	Transport, truck>20t, Euro4,80%LF,default/GLO Mass	0,627	tkm		
Electricity	Electricity mix, AC, Consumption mix,at consumer, < 1kV IE S System – copied from ELCD	0,295	kWh		
Emissions					
Methane from EF	Methane, Biogenic	0,195	kg	Blonk et al. (2023)	
Methane from MM	Methane, Biogenic	0,0549	kg		
N_2O (Direct) from stable	Dinitrogen Monoxide	0,000363	kg		
N_2O (Indirect) from stable	Dinitrogen Monoxide	0,000509	kg		
	Particulates,< 10 um	0,4661	kg		
	Ammonia	0,038	kg		
	NMVOC,non-methane Volatile organic compounds	0,0112	kg		

Process	Agrifootprint category	Qty	Unit	Reference	Comments
OF_Ryegrass-clover seed, organic, at farm gate/FR U					
Outputs					
	OF_Ryegrass-clover seed, organic, at farm gate/FR U	9350	kg	Blonk et al. (2023)	
Inputs					
Land Occupation	Occupation, annual crop	31726,03	m2a		
Energy	Energy,gross calorifc value, in biomass	198000	MJ		
	Carbon dioxide, in air	22194,755	kg	Blonk et al. (2023)	
Inputs					
Organic fertilizer	Organic phosphorus fertiliser, as P2O5 {GLO}| market for organic phosphorus fertiliser, as P2O5 | Cut-off, U	7,415012	kg		
	Organic potassium fertiliser, as K2O {GLO}| market for organic potassium fertiliser, as K2O | Cut-off, U	56,616275	kg		
	Organic nitrogen fertiliser, as N {GLO}| market for organic nitrogen fertiliser, as N | Cut-off, U	4,396376	kg		

	Organic phosphorus fertiliser, as P_2O_5 {GLO}| market for organic phosphorus fertiliser, as P_2O_5 | Cut-off, U	27,886893	kg	Blonk et al. (2023)
	Organic potassium fertiliser, as K_2O {GLO}| market for organic potassium fertiliser, as K_2O | Cut-off, U	68,082862	kg	
	Organic nitrogen fertiliser, as N {GLO}| market for organic nitrogen fertiliser, as N | Cut-off, U	15,296309	kg	
	Organic nitrogen fertiliser, as N {GLO}| market for organic nitrogen fertiliser, as N | Cut-off, U	15,220035	kg	
	Organic potassium fertiliser, as K_2O {GLO}| market for organic potassium fertiliser, as K_2O | Cut-off, U	68,082862	kg	
	Organic phosphorus fertiliser, as P_2O_5 {GLO}| market for organic phosphorus fertiliser, as P_2O_5 | Cut-off, U	27,886893	kg	
Reduced tillage	Soil maintenance, with cover crop 4m/FR U	0,5	hr	
	Rolling, with roller 9m/FR U	0,33	hr	
Transportation	Transporting to farm, with trailer (<15t) heavy tractor/FR U	4,72	hr	
Ryegrass – clover	Ryegrass - clover seed, organic, at farm gate/FR U	20	kg	
Sowing	Sowing or planting, direct seeding/FR U	0,83	hr	

Process	**Agrifootprint category**	**Qty**	**Unit**		**Comments**
Ryegrass – clover	Clover seed, Swiss integrated production, for sowing {GLO}| market for | Cut-off, S - Copied from Ecoinvent	5	kg		
Crushing	Crushing, with shredder or chipper/FR U	0,67	hr		
Emissions to Air, water & Soil					
	Dinitrogen monoxide	0,548628	mg		
	Dinitrogen monoxide	0,64702	mg		
	Dinitrogen monoxide	0,050679	mg	Blonk et al. (2023)	
	Ammonia	3,443468	mg		
	Nitrogen oxides	0,834	mg		
	Chromium	0,014	mg		
	Lead	0,002	mg		
	Lead	0,002	mg		
	Zinc	0,023	mg		
	Phosphate	0,68	mg		
	Cadmium	0.000724	mg		

	copper	0,086	mg	
	copper	0,010384	mg	
	Chromium	0,26	mg	
	Nickel	0,0062	mg	
	Zinc	0,537	mg	
	Nitrate	243,122	mg	
	Mercury	0.0004	mg	Blonk et al. (2023)
	Phosphorous	0,0622	mg	
	Mercury	0.00005	mg	
	Lead	0,0088	mg	
	Nickel	-0,04155	mg	
	Zinc	-1,92	mg	
	Cadmium	-0,00446	mg	
	Chromium	-0,2945	mg	
	Copper	-0,62	mg	
	Mercury	-0,0163	mg	

Process	Agrifootprint category	Qty	Unit		Comments
Oat grain					
Outputs					
Oats	MSCC>Oat grain, at farm/IE Mass	7,64E+03	kg		
	MSCC>Oat straw, at farm/IE Mass	2,75E+03	kg		
Input					
	Water, unspecified natural origin, IE	0.1138	m3	Blonk et al. (2023)	
	Occupation, annual crop	10000	m2a		
	Manure (cow)	518.7+909.7	kg		
	Di ammonium phosphate, as 100% (NH3)2HPO4 (NPK 22-57-0), at plant/RER Mass	52,42	kg		
	Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), at plant/RER Mass	171,6	kg		
	NPK compound (NPK 15-15-15), at plant/RER Mass	85,87	kg		
	Urea, as 100% CO(NH2)2 (NPK 46.6-0-0), at plant/RER Mass	26,95	kg		
	Potassium chloride (NPK 0-0-60), at plant/RER Mass	73.54	kg		
	Lime fertilizer, at plant/RER Mass	400	kg		

Process	Agrifootprint category	Qty	Unit	Comments
	Oat grain, start material, at seed production/IE Mass	265,9	kg	
	Insecticide, at plant/RER Mass	0,0939	kg	
	Fungicide, at plant/RER Mass	1,399	kg	
	Herbicide, at plant/RER Mass	4,598	kg	
	Insecticide emissions, at farm/RER	0,0939	kg	
	Fungicide emissions, at farm/RER	1,399	kg	Blonk et al. (2023)
	Herbicide emissions, at farm/RER	4,598	kg	
	Manure (cow), at farm/RER Mass	6096,7	kg	
	Energy, from diesel burned in machinery/RER Mass	4561	MJ	
	Energy, from deisel burned in machinery/RER Mass	0,0726	MJ	
	Electricity mix, AC, consumption mix, at consumer, < 1kV IE S System - Copied from ELCD	0,05401	MJ	
Emissions to air				
	Carbon dioxide, fossil	176	mg	
	Carbon dioxide, fossil	19,76	mg	

	Dinitrogen monoxide	1,336	mg	
	Dinitrogen monoxide	0,4341	mg	
	Ammonia	3,598	mg	
	Nitrogen monoxide	0.595	mg	Blonk et al. (2023)
	Carbon dioxide, land transformation	4,908	mg	
	Dinitrogen monoxide	1,036	mg	
	Dinitrogen monoxide	0,3368	mg	
	Ammonia	16,01	mg	
	Dinitrogen monoxide	0,9399	mg	
	Dinitrogen monoxide	0,2115	mg	
	Nitrate	112,9	mg	
	Phosphorous	1,041	mg	
	Cadmium	41,63	mg	
	Chromium	20930	mg	
	Copper	3410	mg	
	Mercury	0,8924	mg	

	Nickel	0	mg	
	Lead	335,5	mg	
	Zinc	29710	mg	Blonk et al. (2023)
	Nitrate	87,61	mg	
	Phosphorous	0,8541	mg	
	Nitrate	79,46	mg	
	Cadmium	3355	mg	
	Chromium	243300	mg	
	Copper	13600	mg	
	Mercury	63,35	mg	
	Nickel	19990	mg	
	Lead	23170	mg	
	Zinc	779500	mg	

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