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Sustainability of European cattle farming: Status Quo and ways forward analysed with a farm-level optimisation model

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Kurzfassung

Europa gehört zu den bedeutendsten Rinderproduzenten weltweit und trägt damit zur Ernährungssicherheit und Ökonomie bei. Aufgrund ihrer negativen Umweltwirkung werden jedoch bestehende Produktionssysteme in Frage gestellt. Diese Arbeit bewertet die Nachhaltigkeit europäischer rinderhaltender Betriebe und identifiziert technologische und politische Wege, diese nachhaltiger zu gestalten. Hierzu wird das bioökonomische Optimierungsmodell FarmDyn angewendet.

Zunächst wird das Modell für eine Lebenszyklus-Nachhaltigkeitsbewertung typischer europäischer Rindfleischproduktionssysteme verwendet. Hier zeigt sich, dass der Einsatz von Kälbern aus Milchrassen aufgrund der Allokation von Auswirkungen zur Milchproduktion zu besseren Umweltindikatorwerten und einem geringeren Arbeitsaufwand führt. Beispielsweise ist der Ausstoß von Treibhausgasen (THG) im Vergleich zu reinen Fleischrassen um bis zu 60% geringer. Allerdings sind Systeme mit reinen Fleischrassen aufgrund höherer Rindfleischpreise profitabler.

In einer zweiten Anwendung werden Kurz-Umtriebs-Weide (KUW) und Kreuzungszucht von Rindern (KZR) auf ihren Beitrag zu nachhaltiger Rindfleischproduktion untersucht. Die KUW steigert die Profitabilität und die Arbeitszeitbelastung. KZR mit Milch- und Fleischrassen kann den THG-Ausstoß senken, während KZR mit frühreifen Fleischrassen nur begrenzte Effekte zeigt. Eine Umgestaltung von Betrieben mit KZR mit Milchrassen, KUW und einer angepassten Besatzdichte könnte die Konkurrenz zwischen Lebensmittel- und Futterproduktion erheblich verringern.

Die dritte Anwendung schätzt betriebliche Grenzvermeidungskosten von THG für norwegische Milchviehbetriebe. Die Ergebnisse zeigen, dass eine Reduzierung um bis zu 5% des momentanen THG-Ausstoßes der Betriebe zu Kosten von 200€ pro t CO_2eq möglich ist. Die wirksamste Maßnahme ist die Optimierung der Fütterung hin zu einer höheren Energiedichte, wodurch 8% bis 20% der Emissionen aus der enterischen Fermentation eingespart werden können. Weitere kosteneffiziente Maßnahmen umfassen die Verwendung von Biodiesel und effizientere Gülleausbringtechnologie. Größere Einsparungen werden durch eine Reduzierung der Herdengröße erzielt, angefangen bei Bullen für die Rindfleischproduktion, aufgrund ihrer geringeren Rentabilität.

Angesichts der anhaltenden Umweltauswirkung der Rinderhaltung, ihres ökonomischen Beitrags und ihres sozialen Einflusses sind politische Maßnahmen erforderlich, um Umweltauswirkungen, politische Ziele und Interessen der Landwirte sorgfältig abzuwägen.

Abstract

Europe is among the largest cattle producers worldwide, contributing to food security and the economy. However, the recent public debate has questioned existing production systems due to their adverse environmental effects, such as their contribution to climate change. This thesis assesses the sustainability of European cattle farms and identifies technological and political levers to improve them towards more sustainable means of production. For this purpose, the bio-economic optimisation model FarmDyn is applied.

First, the model is used for a life cycle sustainability assessment of typical European bull beef production systems. Here, it is revealed that using dairy breed calves leads to favourable environmental indicator values and less work time spent on production due to the partial allocation of impacts towards dairy production. For example, systems using dairy breeds for fattening reduce global warming potential (GWP) by up to 60% compared to beef breeds. In contrast, beef-breed systems have higher profitability due to higher beef prices despite higher production costs.

In a second application, the before-established framework is used to test fast rotational grazing (FRG) and crossbreeding (CB) regarding their ability to improve the sustainability of beef production. FRG increased farm profit and production workload through additional fencing efforts. CB with dairy cows and beef bulls was found to decrease GWP, while CB with early-maturing beef breeds showed only limited improvement. Redesigning farms using CB with dairy cows, FRG, and a stocking rate adjusted to the land's carrying capacity could substantially decrease the feed-food competition.

The third application estimates marginal greenhouse gas abatement cost curves for Norwegian dairy and dairy-beef farms. The findings indicate that up to 5% abatement compared to current emission levels of the farms is achievable at costs below 200€ per t CO_2eq. The most effective measure is optimising animal feed rations towards higher energy density, potentially saving 8% to 20% of emissions from enteric fermentation. Other cost-efficient measures include transitioning from fossil fuels to biofuels and adopting advanced manure application technology. However, higher abatement efforts are realised through herd size reductions, starting with bulls for beef production, as they are less profitable.

Given cattle production's prevalent burden on the environment, its contribution to the economy, and its social influence, political action is needed to carefully balance environmental impacts, policy goals, and farmers' interests.

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Abbreviations

BE	Belgium system
BE-BF	Belgium breeder and fattener farm
CAP	Common Agricultural Policy
CB	Cross-breeding
CH_4	Methane
CM	Contribution margin
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CP	Crude protein
DM	Dry matter
EU	European Union
EUR	Euro
FDP	Fossil fuel depletion potential
FADN	Farm Accountancy Data Network
FEP	Freshwater eutrophication potential
FRG	Fast rotational grazing
FR-IT	French-Italian system
FR-IT-B	French breeder
FR-IT-F	Italian breeder
FU	Functional unit
GE-GE	German system
GE-GE-B	German dairy farm
GE-GE-F	German fattener farm
GHG	Greenhouse gas
GWP	Global warming potential
HCC	Human-consumable calories
HCP	Human-consumable protein

HEP	Human-edible protein production efficiency
JÆR	Farm in Jæren
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LU	Livestock unit
MACC	Marginal Abatement Cost Curves
MCDM	Multi-criteria decision-making
ME	Metabolizable energy
MEP	Marine water eutrophication potential
M&R	Farm in Møre & Romsdal
N	Nitrogen
N_2	Gaseous Nitrogen
NEC	EU National Emissions Reduction Commitments Directive
NH_3	Ammonia
NIR	Norway's National Inventory Reporting
NN	Farm in North Norway
N_2O	Nitrous oxide
NO_3-	Nitrate
NO_x	Nitrogen oxides
NOK	Norwegian Kroner
Non-ETS	Emissions not covered by the EU Trading Scheme
ØL	Farm in Østland
P	Phosphorus
PG	Permanent Grazing
$PM_{2.5}$	Particulate Matter Emission
PMFP	Particulate Matter Formation Potential
SLCA	Social Life Cycle Assessment

SR	System Redesign
SX	Sexing
t	Tonnes
TAP	Terrestrial Acidification Potential
TR.flat	Farm in the planes of Trondelag
TR.hill	Farm in the hills of Trondelag
VL	Farm in Vestland
WT	Work time

Chapter 1
Introduction

Europe is among the largest cattle-producing regions in the world. In 2021, around 115 million animals produced 10 million tonnes (t) of beef meat (with bones) and 226 million t of raw milk valued at 107 billion € (FAO, 2023). Cattle are an important commodity for intra- and inter-regional trade, with a combined export volume of 3.6 million t of beef meat and 57.7 million t of milk in individual European countries (FAO, 2023).

Cattle are widespread among European farms. For example, 3.6 million farms kept cattle in 2017 in the European Union (EU), with France and Germany having the largest herds at 19 and 12 million heads, respectively (Hocquette et al., 2018; Ihle et al., 2017). European cattle farms work one-third of the EU's agricultural land with a quarter of the EU's agricultural workforce (Ihle et al., 2017).

The cattle farm structure across Europe is heterogeneous. Large, specialised farms dominate Western Europe, while small mixed farms characterise Eastern states. Cattle-intensive regions, where more than half of the commercial farms keep cattle, are in France, Germany, northern Spain, and Scandinavia (Ihle et al., 2017). The economic return of the EU farms varies between states. In 2020, the net value added per average working unit on dairy and cattle farms ranged between 2,050 € in Romania and 93,160 € in Denmark (EC, 2023).

Cattle are bovines and, therefore, one of the few means to use grass as feed through their complex digestive system. 237 million ha of Europe is covered with temporary and permanent meadows predominantly used by bovine animals (FAO, 2023). Grazing also preserves valuable habitats and semi-natural landscapes (FAO, 2023).

Despite their advantages, their economic importance, and their role in history and culture, cattle have been part of the public debate on environmental externalities. Deforestation induced by the extension of fodder production areas may lead to biodiversity loss; animal wastes can pollute waterbodies through nitrate (NO_3-) leaching and contribute to acidification by gaseous ammonia (NH_3) losses. 73% of the EU 27 NH_3 emissions are credited to livestock production, and 51.3% are caused by cattle (Malherbe et al., 2022). Approximately 200-340 kg of reactive nitrogen (N) emissions are discharged to produce 1 kg of beef meat, 200 times the amount for fruits and vegetables (Westhoek et al., 2015). The high water usage of cattle, feed production, and processing can increase regional water scarcity.

In addition, cattle's contribution to climate change through direct and indirect emissions questions existing production systems. Cattle emit methane (CH_4) during enteric fermentation; their excrements contain N, which leads to emissions of direct and indirect nitrous oxides (N_2O). The usage of fossil fuels to produce inputs and the processing and marketing of products emit carbon dioxide (CO_2). Furthermore, feed production and pasturing can cause indirect emissions of carbon stocks released by land use change (Peyraud et al., 2020).

In 2020, the agricultural sector was responsible for around 10% of the EU's emissions of greenhouse gases (GHG). Roughly 30% of these are CH_4 emissions from enteric fermentation from cattle (EEA, 2022). Combined N_2O and CH_4 from manure management systems and N_2O from the application of manure to soils and manure left on pastures, cattle production in Europe emits 326 million tonnes of carbon dioxide equivalents (CO_2eq) (FAO, 2023). Individual production systems' emission levels vary considerably due to their heterogeneity in farm structure and production conditions (Peyraud et al., 2020).

1.1 Motivation

To meet society's expectations of a supply of meat and milk that does not stress the environment, decision-makers are looking for ways to transform cattle production. Accordingly, sustainable production is becoming a declared policy goal across Europe

(Guyomard et al., 2021). In the EU, the European Green Deal goals are zero net emissions of GHG by 2050, economic growth decoupled from resource use (Fetting, 2020). At its heart is the Farm-to-Fork Strategy, which aims to make food systems fair, healthy, and environmentally friendly (European Commission, 2020). Here, livestock production is meant to reduce its contribution to climate change, limit biodiversity loss and pollution, lower the use of antibiotics, and increase animal welfare.

Existing EU directives already target specific environmental impacts of cattle production. For example, the EU National Emissions Reduction Commitments Directive sets emission ceilings for air pollutants, and the EU Nitrates Directive aims to prevent NO_{3^-} from agricultural sources that pollute ground and surface waters (European Council, 1991; European Commission, 2016). Cattle production is a significant emitter of NH_3 and NO_{3^-} and thereby targeted by both policies (Groenestein et al., 2019).

Furthermore, the EU Commission plans to reduce the dependency on imported feed, especially soybeans, by promoting local feeds and alternative feedstuff such as industry by-products (European Commission, 2019). European countries outside the EU also have policies to account for the environmental impact of cattle production systems. Norway, for example, went into an intentional agreement with the two leading farmers' unions to reduce GHG emissions from the agricultural sector by 5 million t (Norwegian Government, 2019).

The reasoning behind such policy intervention follows the concept of market failure. Market failure can occur when decisions from individuals result in externalities that lead to socially undesirable outcomes. Such externalities can be positive, for example, the preservation of habitats through extensive cattle grazing, or negative, for example, nutrient leaching from cattle’s excrements. Without intervention, farmers have little incentive to either maximise the positive externalities or minimise the negative externalities. Governmental action is meant to prevent such failure. However, the formulation of sound policies is complex for many reasons.

Given the multitude of impacts and their interrelations, policies in the livestock sector need to address multiple objectives across different dimensions of sustainability while considering costs for society and farmers alike. Information on the impacts, interlinkages, and relationships is therefore crucial for decision-makers. It allows to balance, prioritise, and compromise between contrasting policy goals and promote the complementarities in a diverse, complex, and disaggregated sector characterised by heterogenous farming systems (Steinfeld et al., 2006; Hocquette et al., 2018).

Furthermore, the multifunctional character of cattle production can pose a challenge. Multifunctional or joint production refers to the simultaneous production of various outputs. Technical interdependencies in production, non-allocatable inputs, or inputs with a (quasi-)fixed supply are the causes of this (OECD, 2001). The implication of joint production depends on the nature of the relationship and the degree of jointness. Outputs can be classified into commodity and non-commodity outputs. The primary commodities of cattle are dairy and beef products. Non-commodities are non-marketable goods and services, such as landscape conservation through grazing cattle. Outputs can also be interlinked: For example, biodiversity preservation, water quality, and landscape protection can be related and complementary, while biodiversity, agricultural employment, and reductions in environmental externalities from fertiliser usage have a reciprocal relationship, which leads to trade-offs (OECD, 2008). Moreover, dairy and beef production rely on interchangeable inputs like pastures and concentrates for feeding. An isolated consideration of only one commodity could lead to emission leakage from one sector to another (Styles et al., 2018).

Considering the significant contribution of European cattle production to current environmental challenges, particularly climate change, policy intervention seems necessary. As European policymakers increasingly strive for sustainable production, understanding the complexities of cattle farming becomes essential. Information is needed on the multifunctional nature of production. This entails exploration of the intricacies of joint production, specifically a comprehensive understanding of the relationships and trade-offs while also considering the heterogeneity of farms.

1.2 Research aims

This thesis aims to assess the sustainability of European cattle production systems and identify technological and political levers to improve them towards sustainable production. To accomplish this, the single farm model FarmDyn is extended and applied (Britz et al., 2014). FarmDyn originates from a research project on calculating marginal GHG abatement costs on German dairy farms (Lengers et al., 2014). Since then, it has been used and amended in different applications: introducing pig farming and biogas production (Garbert, 2013; Schäfer et al., 2017), impact assessment of environmental policies (Kuhn et al., 2019; Kuhn et al., 2020; Heinrichs et al., 2021; Freytag et al., 2023) and technology assessment (Pahmeyer et al., 2020).

Mathematical programming models are a helpful methodology for ex-ante impact assessments of various technology and policy changes before their implementation. Especially bio-economic farm optimisation models provide several advantages for a sustainability assessment of European cattle production systems. First, optimisation enables depicting farmers' potential decision-making and reactions to different settings (Djekic et al., 2018). The farm level is the critical decision-making unit where the farmer plans management and production (Reidsma et al., 2018). These decisions affect the economic, environmental, and social impacts of production and, ultimately, policies (e.g., Cortignani & Dono, 2015; Reidsma et al., 2015; Viaggi et al., 2010). Second, farm models provide a detailed description of on-farm technology and operations. Technologies can be considered alongside many activities and restrictions, including crop and livestock interactions (Janssen & van Ittersum, 2007). Third, the detailed description of processes and technologies also enables the consideration of farm heterogeneity. The importance of accounting for farm heterogeneity when analysing agricultural production systems is shown in numerous studies (e.g., Mack & Huber, 2017; Renner et al., 2021). Farm-level models offer greater flexibility in capturing such farm heterogeneity than other mathematical programming models (Blanco, 2016). Fourth, the decisions on production programs and related physical flows can be used as an inventory to assess sustainability indicators and externalities of production (e.g., Lengers et al., 2014). The holistic analysis further captures interdependencies among and between impact categories. Furthermore, the effect of varying parameter values on results can be analysed in a sensitivity analysis (Janssen & van Ittersum, 2007). Due to these advantages, farm-level optimisation models are increasingly used for ex-ante impact assessments of technologies and policies. They help inform decision-makers about potential intended and unintended impacts, guiding them towards sustainable production (Reidsma et al., 2018).

As the introduction outlines, European beef-producing farms are highly heterogeneous and cause significant environmental impacts. Besides these impacts, beef production affects sustainability's economic and social dimensions. Therefore, the first research aim targets the sustainability of beef production systems using the FarmDyn model:

I) Assessing the environmental, economic, and socioeconomic performance of three bull beef production systems in Europe using a lifecycle perspective.

The FarmDyn model provides the inventory data needed to perform a Life Cycle Sustainability Assessment (LCSA) in this application. LCSA provides a methodological framework to integrate sustainability's environmental, social, and economic dimensions in assessing a product or service along its life cycle (Zamagni, 2012). Due to the inclusion of multiple indicators, trade-offs and co-benefits between impacts can be identified, allowing for a comprehensive analysis of production systems. All impacts are related to a functional unit, which enables the comparison of heterogeneous systems in terms of their performance. Furthermore, the lifecycle perspective considers upstream impacts, such as the production and provision of important inputs or the transport of animals.

To achieve this comprehensive analysis, major European production systems are identified with consistent system boundaries. These systems are then parameterised in FarmDyn, including segregated systems where different stages of production are spatially separated on distinct farms. Then, indicators for sustainability's environmental, social, and economic dimensions are gathered and related to a functional unit (kg beef meat produced). The multifunctionality of cattle production is also reflected as different outputs are accounted for and impacts are allocated to them according to their specific market price. To include upstream emissions outside the farm gate, the EcoInvent database (Wernet et al., 2016) is amended to the FarmDyn model. A large-scale sensitivity analysis tests the influence of parameter variation in prices, animal traits, and yields. The resulting application of a farm-level optimisation model in the performance of an LCSA is the first of its kind.

The aforementioned environmental implications of European cattle production require action. Reducing emissions at the farm level necessitates considering farm practices under farmers' control (Burbi et al., 2016). According to Laborde et al. (2021), improved farm management practices have the potential to substantially reduce the environmental burden of agricultural production at a low cost. Part of this dissertation is linked to the SustainBeef project, which aims to co-define and evaluate sustainable beef farming systems based on resources non-edible by humans. During the project, several innovations to increase the sustainability of cattle farms were identified and discussed in focus group interviews with farmers and advisors. The two innovations of rotational grazing and crossbreeding have been of particular interest and been selected for further analysis, which leads to the second research aim:

II) Exploring the potential of rotational grazing and crossbreeding in European beef production systems to reduce GHG emissions and feed-food competition.

Rotational grazing refers to the partitioning of pastures into smaller paddocks that are grazed for a limited amount of time before rotating to the next paddock. The periodically high stocking density on the paddock can increase the productivity of existing grasslands through more even grazing and thereby reduce the amount of feed grown on arable land. Animal crossbreeding enables the heterosis effect through the planned breeding of cattle breeds with complementary traits to gain more productive animals. In this instance, the aim is to yield animals especially suited for beef production using grasslands.

The application of FarmDyn allows for the analysis of the potential adoption behaviour of novel management and technologies driven by the economic rationale of a profit-maximising farmer. Cross-breeding and rotational grazing compete with other farming activities for limited resources and are chosen only when they offer greater benefits toward the objective than the alternatives. Compared to more static, scenario-driven engineering approaches, this enables pointing out potential shortcomings in the adaptation behaviour of farmers, including unforeseen adjustments to farm management. To further boost the utilisation of the innovation, the analysed exemplary production systems are redesigned in their production focus while keeping the main assets and structures as is. The LCSA framework from Chapter 2 is adapted to estimate potential impacts, offering indicators across the three dimensions of sustainability. Finally, a sensitivity analysis accounts for varying yields, stocking rates, and animal traits.

As mentioned before, there is a large potential to lower GHG emissions at the farm level. Furthermore, technical abatement measures have the advantage of diminishing adverse effects on food production (Bakam et al., 2012). However, their adoption by farmers without political intervention is questionable as they bear additional costs and the externalities of GHG emissions are largely not internalised into farmers' economic decisions. Furthermore, selecting suitable mitigation options for policymakers and farmers requires information on potential emissions savings and these related costs (Fellmann et al., 2021). Furthermore, mitigation efforts need policy coherence to minimise trade-offs in contrasting policy goals, notably maintaining farm income (Di Gregorio et al., 2017). A common methodology to rank and portray abatement options in their economic efficiency is Marginal Abatement Cost Curves (MACC) (De Cara & Jayet, 2011). In deriving MACC for agricultural production, the heterogeneity in the biophysical and economic circumstances of affected farmers plays an important role, necessitating a disaggregated analysis (Fellmann et al., 2021). Farm-level models are built to represent heterogeneity and can capture specific farm-level technology, detailed emission accounting indicators and agricultural policies directed to the farm level.

Therefore, the third research aim is:

III) Quantifying marginal greenhouse gas abatement costs of Norwegian dairy farms considering farm heterogeneity and existing agricultural policy.

The FarmDyn model was initially built to calculate the MACC of German dairy farms (Lengers et al., 2013). Here, MACC are estimated for Norwegian dairy farms. Dairy production makes up a relevant share of the GHG emissions in Norway's agricultural sector and is part of existing reduction efforts. However, a detailed analysis of the potential of reduction-specific measures and their costs is still missing.

To fill this gap, FarmDyn is parameterised to Norwegian conditions through extensive changes, including changed prices, yields, and production technology. This also covers a detailed description of the current Norwegian agricultural policy, including degressive subsidy payments for different types of cattle, pastures and arable land, locally differentiated subsidies, price premiums, agri-environmental measures and fertiliser restrictions. In addition, the GHG calculation methodologies is updated, including detailed estimations of methane emissions from enteric fermentation considering changes in feeding and the addition and update of GHG abatement measures. The resulting tool is applied to a subset of seven dairy farms selected through k-medoid clustering from Norway's Farm Accountancy Data Network (FADN). The smaller farm sample allows for a descriptive analysis of the results while still capturing the sector's heterogeneity.

1.3 Proceedings

The thesis is structured as follows: Chapter 2 presents an LCSA of three typical European beef production systems. In Chapter 3, rotational grazing and crossbreeding as options for beef production to reduce GHG emissions and feed-food competition at the farm level are analyzed, while in Chapter 4, MACCs of Norwegian FADN dairy farms are calculated. Eventually, chapter 5 concludes with the major contributions and the outlook.

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Chapter 2
Life Cycle Sustainability Assessment of European beef production systems based on a farm-level optimization model[1]

Abstract.

The European Union (EU) is among the largest beef producers in the world. Besides the economic turnover, beef production causes adverse environmental impacts such as climate change. The sector is known for high heterogeneity in production systems, partly explained by different natural and economic conditions. This study assesses the environmental, social, and economic performances of three typical beef production systems in the EU at the farm level. The farm optimization model FarmDyn is used in this study to carry out a Life Cycle Sustainability Assessment (LCSA) from cradle to farm gate; combined with a sensitivity analysis on prices, yields and animal traits. The assessed systems are a Belgian suckler cow farm that fattens its own offspring (BE); a system where calves raised in a French suckler cow farm are fattened on a farm in Italy (FR-IT); and a system where dairy bred calves from one farm are fattened on another farm, both located in Germany (GE-GE). The functional unit is 1 kg of carcass weight from young bulls. In addition to several environmental impact categories, the gross margin is estimated as an economic indicator. The social performance is measured with on-farm workload differentiated by tasks, and human calorie and protein conversion used

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for production. GE-GE performs better than the other systems in the environmental indicators because emissions are partially allocated towards dairy production. FR-IT shows the highest gross margin due to a higher beef price. BE and FR-IT use less human-consumable feed, as both systems employ grasslands and by-products for animal feeding. The sensitivity analysis identifies the price of beef and calves, the yield of roughage crops, and the weight and age of animals as major factors influencing the results. FarmDyn proves useful to perform LCSA of beef production on a farm-level as it integrates environmental, economic, and social indicators in a consistent framework, while considering price effects and farmers' behaviour in the context of farm heterogeneity and variability in management practices. Results thus provide valuable information to inform not only farmers' decision but the debate of sustainable beef production in the EU.

Keywords: *farm model; life cycle assessment; livestock; optimization model; sensitivity analysis; sustainability*

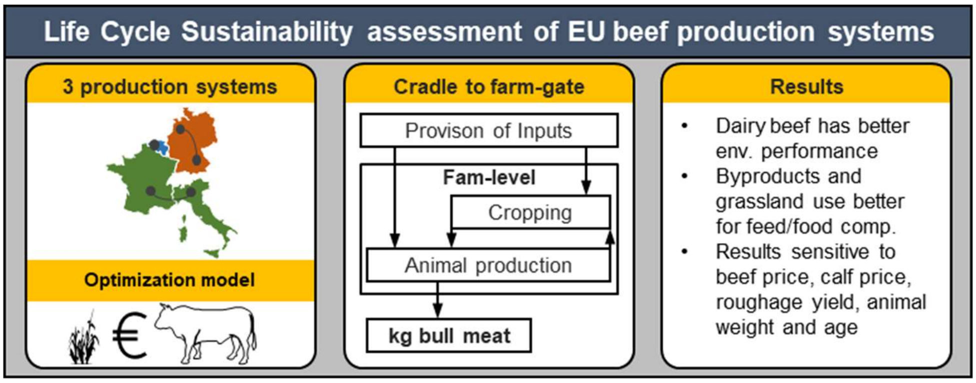

Figure 2.1 Graphical abstract

2.1 Introduction

Livestock production causes 13% of the global greenhouse gas (GHG) emissions (Herrero et al., 2016), around 33% of nitrogen (N) pollution (Uwizeye et al., 2020) and uses more than 40% of global arable land for feed production (Mottet et al., 2017). Concerns arise on the over-consumption of meat as food, given the low calorie-conversion efficiency of livestock (Wilson et al., 2019). According to Cassidy et al. (2013), an additional four billion people could be fed if all arable land were used to directly grow food instead of fodder or biofuels. However, livestock production contributes to the fight against hunger through the conversion of non-edible feedstuff into food for human consumption (Smith et al., 2013). Furthermore, the livestock sector contributes to the economy with a global production value of 1.2 trillion US$ in 2018 (FAO, 2020). Despite the disadvantages of livestock production, the global consumption of livestock products has been rising (FAO, 2020) and plays a crucial role in reaching the United Nations' Sustainable Development Goals (Mehrabi et al., 2020).

A large share of the global livestock production is concentrated in the European Union (EU), e.g., 20% in 2018 (FAO, 2020). In 2017, the EU-28 agricultural sector generated 10% of the region's total GHG emissions with a production value of 170 billion €, with around 4 million people employed in livestock farms (Peyraud & MacLeod, 2020). Within the EU, cattle constitute the largest share of the livestock population at around 50% of the total livestock units, with France, Germany and Italy having the biggest herds (Cook, 2020). Beef slaughtered in EU slaughterhouses amounts up to 6.8 million tonnes carcass weight while the largest share is estimated for bulls (34%), followed by cows (30%) and heifers (16%) (EUROSTAT, 2021). Bull meat production systems in the EU are characterized by a high degree of heterogeneity. Systems differ by origin and breed of the animals, age and weight at slaughtering as well as the kind and origin of feed used (Hocquette et al., 2018). The highest stocking density of fattening farms can be found in the Benelux states and Northern-Italy (Ihle et al., 2017).

A common methodology to examine the environmental sustainability of agri-food products is Life Cycle Assessment (LCA) (Nguyen et al., 2010). The LCA framework can be extended to cover the economic and social dimensions, i.e., through Life Cycle Costing (LCC) and social LCA (SLCA). LCC is often applied to estimate costs and profits (Florindo et al., 2017), while SLCA aims to assess impacts of production on the workforce, the local community, consumers, value chain actors, and society (Achten et al., 2020). Life Cycle Sustainability Assessment (LCSA) provides an integrated methodological framework based on the three-pillar concept of sustainability first mentioned in the Brundtland report that combines LCA, LCC and SLCA (Zamagni, 2012).

Several studies estimate environmental impacts of beef production in the EU, highlighting the role of emissions from enteric fermentation, fodder production and manure management (e.g. Angerer et al., 2021). Kamilaris et al. (2020) assessed the economic profitability of different beef production scenarios alongside their environmental sustainability. Bragaglio et al. (2018) added the protein conversion efficiency to account for the societal concern of feed vs. food competition in their LCA of beef production in Italy. Yet, there are no examples of a LCSA application to European beef production systems.

LCAs are generally conducted in a static setting, which does not consider the adaption of farmers to changing conditions and their potential consequences (Lan & Yao, 2019). In contrast, mathematical modelling is a tool that captures decision-making, inter alia, in food production systems (Djekic et al., 2018). For instance, farm models, like the FarmDyn model, focus on a farm-scale analysis and are frequently used for assessing environmental impacts (Britz et al., 2021). Their scope at the farm-level as the key decision-making unit allows capturing economic, environmental, and social impacts of management scenarios and policies (Reidsma et al., 2018). In the LCA context, optimization models can provide insights on changes of the environmental performance of agricultural systems due to farmers' adaptation to changing conditions such as price or yield changes (Veysset et al., 2010). By definition, bio-economic models capture not only biophysical but also economic flows within and between farms and, therefore, are well suited to add the economic dimension to LCA (Crosson et al., 2011). The advantages of optimization models can also be utilized in large-scale sensitivity analysis (Pahmeyer et al., 2020). When carrying out LCA, methodological choices and input data lead to uncertainty that affects the reliability of the results and is commonly assessed by means of sensitivity and uncertainty analyses (Escobar et al., 2014). However, the potential of bio-economic farm models to carry out both LCSA and LCA remains underexplored.

The goal of this study is to assess the environmental, economic, and social performance of three beef production systems in the EU within a LCSA framework. The FarmDyn model is applied to assess sustainability trade-offs and benefits, while considering variability in prices, yields and animal performance, as well as farmers' behaviour in the different geographical contexts. The ultimate goal is to identify potential levers to increase the sustainability of typical EU beef production systems on a farm-level, informing cleaner production strategies for farmers and policy initiatives towards more sustainable beef production in the EU.

2.2 Material and Methods

The LCSA is carried out according to the ISO standards 14040/44:2006 (ISO, 2006a; ISO, 2006b), which include the following steps: goal and scope definition, life cycle inventory (LCI) analysis and life cycle impact assessment (LCIA).

2.2.1 *Goal and scope definition*

The goal of this study is to compare the social, economic and environmental performance of three typical beef production systems in the EU, as observed in major producing countries, namely France, Germany, Italy and Belgium. The systems are defined from cradle to farm gate based on data from one year (2017), covering several representative farms that were selected from the Agri benchmark network (Chibanda et al., 2020), the International Farm Comparison Network (Hemme et al., 2000) and the SustainBeef project (Mosnier et al., 2021). They were chosen for being representative of dominant production systems in the EU. Impacts are calculated for each production system and each farm within a system separately. The functional unit (FU) is one kg carcass weight from slaughtered bulls. Carcasses from bulls constitute a different product compared to other cattle (heifers, bullocks, cull cows), given the different product qualities and prices. Co-products of bull production in the analysed systems are female calves (either sold, used for replacement or sold as heifers, depending on the system) and cull cow beef. In dairy herds, milk is also produced alongside the calves. Economic allocation is applied to allocate the impacts between the co-products. It is the preferred method for allocation because the necessary information on prices and economic flows is readily available in the used modelling framework. Furthermore, the complexity of the systems makes it difficult to consistently define causal relationships of physical flows throughout the different sub-steps (Mackenzie et al., 2017). The allocation is thus based on revenues. The specific prices are taken from the farm data described below. Where no exogenous market price exists, the optimization model is used to provide the shadow prices for the economic allocation (Seidel & Britz, 2020).

The three systems are described below. Key characteristics are summarized in Table 2.1.

- The first system represents beef production in Wallonia, Belgium (BE). It consists of one single farm that breeds and fattens (BE-BF) animals of the Belgian Blue breed on a mixed diet of silage, beet pulp, and bought and self-produced concentrates. While suckler cows are grazing during their lifetime, bulls are fattened indoors. Besides beef production, the farm grows rapeseed, cereals and sugar beet as cash crops. 48% of the Belgium suckler cows are managed on farms with comparable herd size in Wallonia (Eurostat, 2016).

- The second system (FR-IT) starts with a suckler cattle farm in the Massif Central, France (FR-IT-B). It keeps a herd of suckler cows of the Saler breed that are cross-bred with bulls of the Charolais breed. A portion of the herd is used to breed pure Salers-animals for replacement.

The mountainous conditions only allow for permanent grasslands. Therefore, the feed consists of grazing, hay and bought concentrates. 16% of the French suckler cow herd is located in the Auvergne-Rhône-Alpes region (Eurostat, 2016). The male offspring is transferred 800 km via lorry to Veneto (Italy) after weaning. The Italian farm (FR-IT-F) fattens the bulls with high daily weight gains (around 1.3 kg/day). The diet consists of maize silage as the main crop grown, beet pulp and concentrates. 31% of the bulls in Italy are managed on farms with comparable herd size in Northeast Italy (Eurostat, 2016).

- The third system (GE-GE) starts with a dairy farm in Bavaria, Germany, which has a herd of Simmental Fleckvieh dairy cows (GE-GE-B). The farm produces milk, calves and grows fodder and cash crops, together with grasslands. Cows are fed a diet of maize and grass silage with complementation of concentrates. 16% of the German dairy cows are managed on farms with comparable herd size in Bavaria (Eurostat, 2016). The 6-week-old male offspring is transported over 600 km via lorry to the North-West of Germany. The second farm (GE-GE-F) is involved in weaning, fattening and cash crop production. The weaning and fattening are based on a diet of maize silage and bought concentrates. 14% of the bulls in Germany are managed on farms with comparable herd size in North-Rhine-Westphalia (Eurostat, 2016).

System	BE	FR-IT		GE-GE	
Farm [a]	**BE-BF**	**FR-IT-B**	**FR-IT-F**	**GE-GE-B**	**GE-GE-F**
Country	Belgium	France	Italy	Germany	Germany
Location	Wallonia	Massif Central	Veneto	Bavaria	North Rhine-Westphalia
No. sold male animals per year [b]	56	38	324	48	280
No. of cows	115	79	-	120	-
Breed	Belgian Blue	Charolais & Salers	Charolais & Salers	Simmental	Simmental
Live weight at butchering [c]	640 kg	380-390 kg	700 kg	85 kg	720 kg
Age at selling [d]	20 months	9 months	17 months	1.5 months	18.7 months
Dress percentage	70 %	-	57 %	-	55 %
Arable land	49 ha	-	33 ha	39 ha	70 ha
Grassland	61 ha	96 ha	-	60 ha	-
Other activities generating co-products	cash crop	-	-	dairy, cash crop	cash crop

Table 2.1 Overview on the systems and farms under analysis. “a” Indices B and F stand for breeder and fattener. “b” for breeding farms, this is the number of sold male calves, for fattening farms this is the number of butchered bulls. “c” for breeding farms, this is the weight at which

the bull calves are transferred to the fattening farm. “d” for breeding farms, this is the age at transfer of bull calves, for fattening farms this is the age at butchering.

The system boundaries include all stages to deliver 1 kg of bull carcass weight from cradle to farm gate. As can be seen in Figure 2.2, this refers to feed production (cultivation, seeding, fertilizing, pesticide application, liming and harvest), breeding (recreational activity in the herd, care taking of cows, heifers and calves), and fattening, as well as transport of animals between farms in FR-IT and GE-GE. Impacts associated with the production of agricultural inputs and services are included within the system boundaries, i.e., machinery production and operation, energy, concentrates, fertilizer and pesticide production.

In BE and the breeding farm in FR-IT, manure is handled as solid manure, whereas on the other farms, it is handled as liquid. In all systems, the amount of manure generated per FU is reused for fertilization and does not constitute a by-product from the system. Impacts from transport of the bulls to the slaughterhouse as well as from processing of the meat are excluded from the system boundaries.

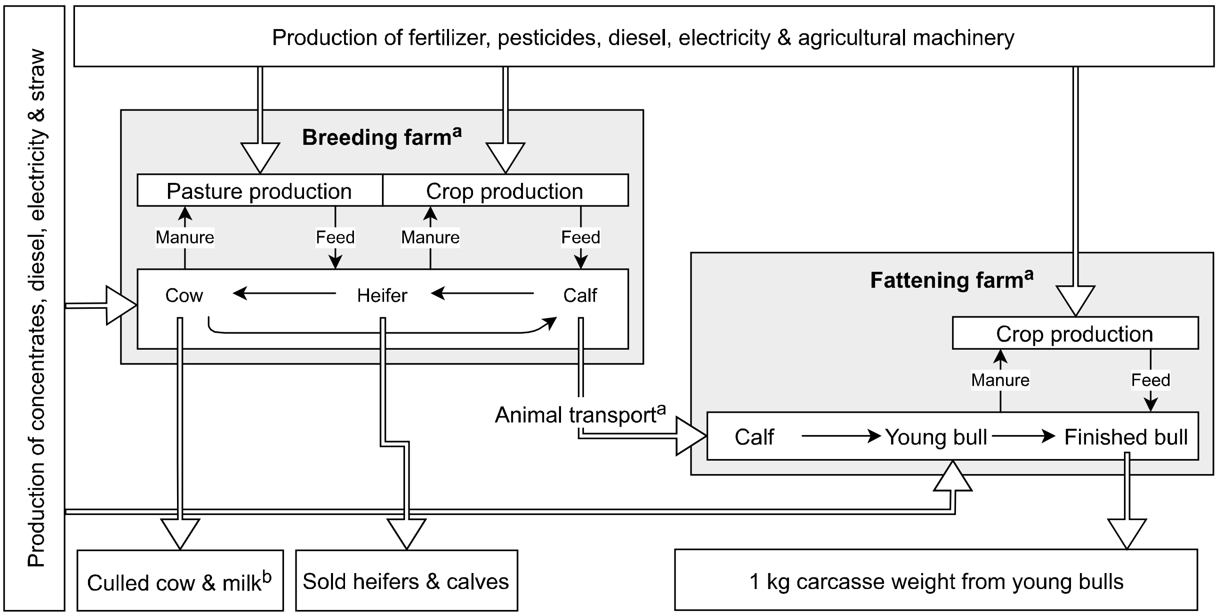

Figure 2.2 System boundaries of the analysed beef production system. “a” in the Belgium system breeding and fattening are integrated in one farm which spares animal transport. “b” milk is only a co-product on the dairy farm of the German system.

2.2.2 *Life cycle inventory*

The LCI of the inputs and outputs entering and leaving the system boundaries is generated with the optimization model FarmDyn (Britz et al., 2014). FarmDyn captures economic as well as bio-physical processes. The model simulates farm management options, while the outcome represents the economically optimal distribution of agricultural activities and practices, maximizing the farms profit. FarmDyn was originally developed to enhance sustainability of agricultural systems and was recently expanded to depict cattle farming systems in the European context (Kuhn et al., 2020; Pahmeyer & Britz, 2020). Each farm operates as an individual entity, which means that the farm program (including cash crop and dairy production) is optimized subject to boundary conditions such as prices or farm endowments. Farmers' decisions include, inter alia, which animals to keep, how to feed them, which crops to grow and how to fertilize them. As for animal production, FarmDyn captures herd demographics (calving, raising periods, replacement, and selling) per month. The feed requirements are calculated using the methodology of the feed planning tool Zifo2 (LfL, 2016), by considering dry matter, fibre, protein, energy and nutrient intake as well as animal performance and lactation periods. The requirements can be met with a variety of bought and self-produced feedstuff. The composition of nutrients in each feed is taken from LfL (2020). The resulting feed use is shown in Table S1 in the appendix.

Crop production options are farm-specific by considering the respective yields, fertilizer needs and land endowments. FarmDyn includes both cash and fodder crops, namely wheat, barley, rapeseed, sugar beet, and maize silage. Grassland is differentiated by different means of harvest (silage, hay, baling, grazing), seasonality, productivity and quality of the harvest.

On-farm emissions from the optimal activities after profit maximization are estimated according to the methods specified in Table 2.2, including methane (CH_4), ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), particulate matter emission ($PM_{2.5}$), nitrate (NO_3-) and phosphorus (P). Emissions arising through the production of major farm inputs are based on the Ecoinvent database version 3.6 (Wernet et al., 2016). These refer to the provision and transport of externally bought feedstuff, bedding material, fertilizers, pesticides; as well as diesel used in agricultural machinery for field and stable operations including cultivation, harvest, manure management and spreading. The field and stable operations cover provision and operation of machines as well as energy consumption. In FR-IT and GE-GE, impacts on the breeding farms are calculated per kg of live weight of transferred animals, which are subsequently implemented as emission factors into the optimization problem of the fattening farm.

Price data and work endowments are modelled based on the farm data from the Agri benchmark network (Chibanda et al., 2020), the International Farm Comparison Network (Hemme et al., 2000) and the SustainBeef project (Mosnier et al., 2021). Prices not covered in the above-mentioned sources as well as work time requirements are taken from farm planning data (Achilles, 2016). The human-consumable share of protein and calorie content of the feedstuff and meat are based on Laisse et al. (2016), Ertl et al. (2016) and Wilkinson (2011).

Source / Sub-source	Pollutant	Methodology	Tier[a]
Enteric fermentation	CH_4	IPCC (2019)	2
Manure management	CH_4	IPCC (2019)	2
	NH_3, N_2O, NO_x, N_2	EEA (2016)	2
	Particulate matter	EEA (2013)	2
Pasture	CH_4	IPCC (2019)	2
	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field & Pasture / Manure application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field & Pasture / Fertilizer application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field / Lime application	CO_2	IPCC (2019)	1
Field / Crop residues	N_2O, N_2	IPCC (2019)	1
Field	Particulate matter	EEA (2016)	1
Field & Pasture	NO_3^-	Richner (2014)	
	P	Prasuhn (2006)	
Indirect N_2O	N_2O	IPCC (2019)	1

Table 2.2 On-farm emissions included in the environmental life cycle inventory and associated estimation methods. [a] In IPCC (2019) tiers represent three different levels of methodological complexity with tier 1 being the basic method and tier 3 being the most complex method.

2.2.3 *Life cycle impact assessment*

The LCIA employs the ReCiPe methodology to quantify the following environmental impact categories at the midpoint level (hierarchist perspective) (Huijbregts et al., 2017): global warming potential (GWP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine water eutrophication potential (MEP), particulate matter formation potential (PMFP) and fossil fuel depletion potential (FDP). These have been identified as the most relevant categories for the based on a comprehensive literature review of LCAs on beef production by de Vries et al. (2015).

The economic performance is measured with the contribution margin (CM) per kg of carcass weight. The CM is the revenues from a product deducted by variable costs to produce such product. This includes revenues from sold beef, costs of buying concentrates, costs of producing roughages, feed costs for rearing, operation and maintenance of machinery, costs of buying animals, variable stable costs and other variable costs. Roughage production costs are measured based on the shadow prices given by the model (Seidel & Britz, 2020).

As for the social performance, working time (WT) on farm per FU is considered, differentiated by type of work, i.e., feeding and taking care of the herd, work for calving, field work, stable maintenance, fertilization and management and office work. Further social indicators considered are the human-consumable calories (HCC) and protein (HCP) used to produce one kg carcass weight. The indicators are included to represent the contribution of beef production to human nutrition as this has been an ongoing societal debate (Mosnier et al., 2021).

2.2.4 *Sensitivity analysis*

FarmDyn allows performing a global all-at-once sensitivity analysis to examine the influence of parametric uncertainty on the LCA results. The following parameters involved in the economic optimization as well as allocation are varied: the beef price, the price of calves and weaned calves, the milk price, and the price of concentrates. Additionally, the spatial and biological variability in the systems is considered through variations in the yield of major roughage crops (grass and maize) and animal parameters such as the weight and age at butchering, and the weight of weaned calves (Table S2 in the appendix). Using Latin Hypercube Sampling, a sample of 1,000 draws with simultaneously changed levels of the aforementioned parameters is created, covering the full range of possible factor level permutations. Because the distributions of the varied parameters are unknown, uniform distributions without correlations are assumed. In FR-IT and GE-GE, the spatial and temporal separation of the farms are considered by using separate sets of 1,000 draws on each farm for crop yields and concentrate prices, respectively. The remaining parameters are similar on the farms in the systems. For each draw, the management decisions on each farm are optimized considering the changed parameters. The results of each optimized farm are combined in a single data frame for each system and are then rescaled to have a mean of zero and a standard deviation of one. This standardization allows the comparison of measurements that have different units. The data frame is analysed through a regression analysis via ordinary least squares. The resulting regression models are considered as meta-models and indicate the relative influence of the parameters on the results.

2.3 **Results**

2.3.1 *Sustainability assessment*

GE-GE shows the lowest values across all environmental impact categories, followed by FR-IT and BE (Figure 2.3). BE has a GWP of 32.3 kg CO_2eq. per FU, compared to 27.7 kg in FR-IT and 12.0 kg in GE-GE. In the latter, impacts from the breeding stage are partially allocated to the co-product milk. FR-IT performs better than BE due to the shorter lifespan of the animals.

Enteric fermentation constitutes the largest source of GWP across systems (46.5% - 62.4 %). Second largest GHG emission sources are input production in GE-GE and FR-IT, and on-field emissions in BE, all accounting for >20% of the GWP, respectively. This is due to the larger share of self-produced feeds in BE. In FR-IT and GE-GE imported concentrates add emissions (included in upstream input production).

The FEP sums up to 6.78 g P eq. per FU in BE, 5.67 g in FR-IT and 1.33 g in GE-GE. The greatest contribution to FEP in BE is input production, specifically imported concentrates, with a share of 55.3%. In FR-IT, emissions from pastures (76.5%) dominate because of more grazing on the breeding farm. In GE-GE, on-field emissions account for the largest share of FEP (62.4 %) as maize silage is grown, which is prone to nutrient loss.

MEP is related to N leaching from fields and pasture, and NH_3 emissions from the concentrate production and manure management. Total emissions of MEP sum up to 48.6 g N eq. per FU in BE, 33.3 g in FR-IT and 26.3 g in GE-GE. In BE, crop production for self-produced feed accounts for the largest share of the impact (58.7%). In FR-IT and GE-GE, the largest share is associated with input production (>37%), specifically imported concentrates.

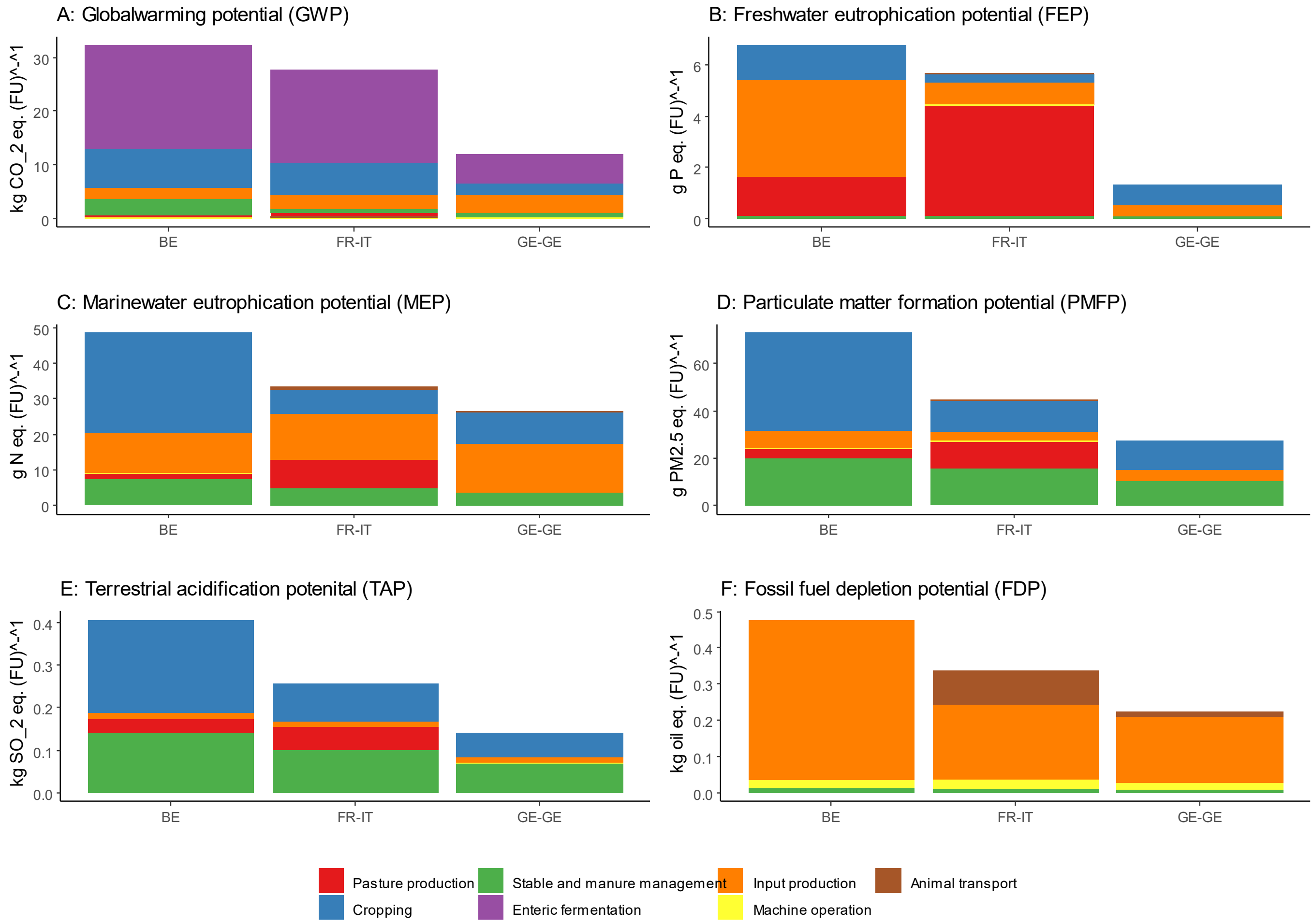

Figure 2.3 Environmental impacts of the beef production systems per kg of bull carcass. BE indicates the Belgium system, FR-IT the French-Italian system and GE-GE the German system. FU stands for 1 kg carcass weight from slaughtered young bulls

The PMFP is estimated at 72.9 g in BE, 45.1 g in FR-IT and 27.3 g PM eq. per FU in GE-GE. The TAP sums up to 0.40 kg in BE, 0.26 kg in FR-IT and 0.14 kg SO_2 eq. per FU in GE-GE. Both PMFP and TAP are mainly caused by NH_3 emissions. Crop production and manure management are the prevailing emission sources in all systems. The allocation to the co-product milk leads to a better performance of GE-GE. FR-IT performs better than BE due to the shorter lifespan of the animals. The contribution of pastures to the PMFP and TAP in FR-IT is associated with the grazing in the breeding farm.

As for FDP, BE consumes 0.48 kg oil eq. per FU, followed by FR-IT (0.34) and GE-GE (0.23). Provision of inputs accounts for the largest share across systems. The transport of live animals in FR-IT contributes 28.1% to overall FDP compared to 7.11% in GE-GE because of a longer transport distance and higher weight of the transferred animals in FR-IT.

2.3.2 *Economic and social indicators*

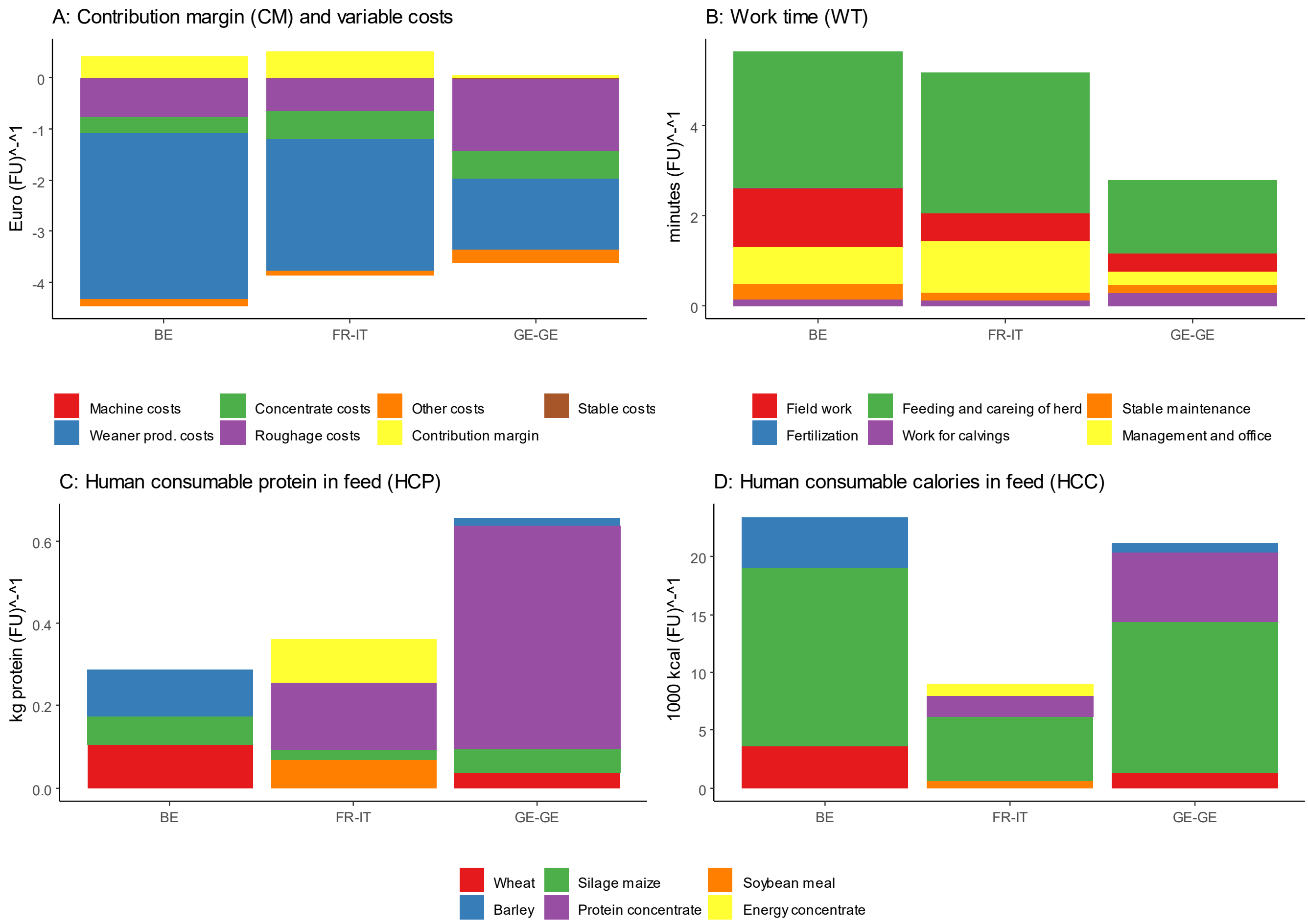

Figure 2.4 Economic and social indicators assessed with FarmDyn for the three systems. BE indicates the Belgium system, FR-IT represents the French-Italian system and GE-GE the German system. FU stands for 1 kg carcass weight from slaughtered young bulls

The CM per FU is estimated at 0.39 € in BE, 0.50 € in FR-IT and 0.03 € in GE-GE. In BE and FR-IT, weanling production with suckler cows leads to the largest cost share with 71.6% and 66.0%, respectively. In GE-GE, calves are bought at a young age from dual-purpose dairy breeds resulting in lower costs (38.1%). In GE-GE, roughage production accounts for the largest share of costs with 38.3%. Roughages are produced on arable land that bares opportunity costs because of the competition with cash crops. Feed concentrate costs are higher in systems with intensive fattening (FR-IT and GE-GE) because of the higher nutrient need for the higher weight gain.

As for the social performance, BE entails the highest workload with 5.63 minutes per FU, followed by FR-IT (5.17) and GE-GE (2.79). In GE-GE, less time is spent on calf production compared to BE and FR-IT because of the allocation towards milk production. The routine of sustaining the herd including feeding constitutes the largest share of workload, followed by field and management work. In BE, the WT is longer because cereals for feeding are produced on-farm. FR-IT entails additional workload compared to BE and GE-GE because there are no shared efforts with other farming branches, like management work.

All systems are net protein- and energy-consumers, meaning that more human-consumable protein and energy are fed than produced. In BE, 0.29 kg human-consumable protein are fed per FU, followed by FR-IT with 0.36 and GE-GE with 0.66. BE and FR-IT benefit from the high intake of grass, which offers a source of protein non-edible by humans. GE-GE has the highest HCP. Here, bulls receive maize as roughage. Since maize is rich in energy, diets must be balanced by adding protein in the form of concentrates which have a high share of human consumable protein.

FR-IT has the lowest HCC at 8,900 human-consumable kcal in the feed per FU, followed by GE-GE at 21,110 and BE at 23,300. The age of the animals determines the comparative result because the energy required for maintaining their metabolism adds up over the lifetime of the animals. In addition, the feeding of concentrates as energy supplement and the larger share of maize silage in the ration further reduce the efficiency in BE and GE-GE. In FR-IT, beet-pulps (considered as non-consumable by humans) are used to a larger extent, increasing the efficiency.

2.3.3 *Sensitivity analysis*

The regression output of all meta-models including R^2, adjusted R^2, Residual Std. Error and F-Statistic is shown in the appendix table S3-S5. This sub-section focuses on GWP, CM, and WT, as representation of the environmental, economic, and social dimension. The beta coefficients of the regression models for GWP, CM and WT and the 95% confidence interval are shown in Figure 2.5.

The beef price is among the factors with the greatest influence on the indicators. In all systems, a higher beef price leads to a higher CM as this implies higher revenues. In BE, a higher beef price leads to a higher GWP and WT because more emissions and work time are credited to beef production in the allocation. In FR-IT, the beef price has little influence on the GWP and WT as the fattening is limited by the endowment of stables and hence the herd size is constant with increasing prices. Furthermore, it is a specialized fattening farm and no allocation is applied.

Variation in the animal weight impacts the performance of all systems. A share of the costs and work tasks are constant per animal. When these are related to a higher weight per animal it results in higher CM and lower WT per FU. A higher share of concentrates in the animals' ration is needed to sustain the higher weight gain, causing additional emissions that increase GWP, e.g., in GE-GE. However, the efficiency gain can outweigh these emissions, overall reducing GWP per FU, e.g., in BE. With a higher weight, the revenues of animals increase. A higher revenue for bull calves leads to higher emissions and time associated with the bull-calf production during the breeding stage due to allocation. The higher price for the heavier calves bares higher costs on the fattening farm and causes a lower CM. A higher price of calves and weaners can also lead to less bulls fattened due to higher costs on the fattening farm, e.g. in GE-GE. Less bulls fattened implies that costs and labour are distributed over less output, which decreases CM and increases WT per FU. Furthermore, the self-produced roughages can be utilized better, which reduces GWP.

With a higher concentrate price, concentrates are used in smaller amounts, hence reducing GWP. At the same time, the higher prices translate into higher feed costs, which slightly reduces the CM. The smaller amount of concentrates increases the relative share of on-farm produced feed, which increases the WT.

The impact of changes in yield of maize and grassland depends on how the yield is used: If additional yield is used to replace low-emission concentrates, the GWP rises (e.g. in FR-IT), if it is replaced with feedstuff with a high emission load the GWP decreases (e.g. maize yield in BE). In all cases, increasing yields results in reduced feed costs and increased CM. WT increases with higher amounts of self-produced feed. However, WT savings are also possible, when the land is better utilized or the additional yield is utilized in grazing, which spares feeding time.

Figure 2.5 Tornado diagram showing the influence of each parameter in the sensitivity analysis on the results in terms of global warming potential, contribution margin and working time. The standardized coefficients indicate the relative importance of each coefficient in the related regressions. The unit of measurement is one standard deviation. The error bars indicate the 95% confidence intervals. Factors marked with a ‘*’ are specific to fattening farms.

2.4 Discussion

The results suggest that the system fattening dairy breed bulls is favourable for the analysed environmental indicators compared to the fattening of beef breed bulls. This is in line with previous findings, for example Nguyen et al. (2010). Carbon sequestration through grassland production is not considered, which could improve the performance of grass-based systems. However, recent research by Hammar et al. (2022) found that a forage-grain beef system resulted in lower GWP compared to an extensive grazing system, even with consideration of carbon sequestration. Still, cattle can be important to sustain current carbon pools under grassland (Conant et al., 2017). Huerta et al. (2016) found extensive systems to outperform intensive systems in several environmental impact categories, indicating, that the results depend on assumptions, used indicators, the location and further characteristics of the analysed system.

A comparison of the results with the literature can be found in the appendix (S6) including information on the FU and the scope of the respective studies. Here the FU is kg carcass weight from slaughtered bulls without the consideration of slaughtering and retail. This inconsistency was chosen as it allows the consideration of different dressing percentages of the different cattle breeds while compromising on the comparability with other studies. However, the contribution of the slaughtering and retail stage on the entire life cycle is reduced compared to the agricultural stage (e.g., Huerta et al., 2016).

A major contribution of this study is that it includes indicators beyond the common environmental impact categories in LCA to assess and compare the sustainability of beef farms under an LCSA approach. The results show that the system with dairy breed bulls (GE-GE) has the lowest CM and the highest HCP pointing at a trade-off between environmental and other sustainability indicators. Kamilaris et al. (2020) found that intensive systems had a lower GWP, too, but their research shows that intensive systems were more profitable. The contrasting results are caused by a higher beef price in FR-IT and BE. A high HCP is also found in the literature (Bragaglio et al., 2018; Wiedemann et al., 2015).

In this study, WT, HCC, and HCP are proposed as social indicators in the LCSA. Due to the novelty of the approach, comparison to the existing literature is limited. The WT is calculated using German farm planning data (Achilles, 2016), which does not necessarily cover all particularities of the analysed systems at the same level of detail as for environmental and economic indicators. However, the data enables consideration of economies of scale of stables, different mechanization levels and plot sizes. The WT indicator would benefit from a detailed representation of the work types and a weighting of tasks by, for example, health hazards, employment potential or personal fulfilment of the workers. In addition, WT spent in upstream processes like the production of inputs should be included to gain insight on affected stakeholders outside the farming community and align with the scope of the LCA. Other indicators of societal concern could be animal welfare or human health (Paris et al., 2022). Implementing these kinds of indicators in FarmDyn is difficult as quantifiable metrics and databases are not readily available.

The results indicate the potential of farm-level models in the application for LCSA as they offer the technical detail to capture farm heterogeneity and present a framework to integrate economic and social indicators. Another advantage is the utilization of the linear optimization to obtain shadow prices where information on market prices is scarce, e.g., the costs of roughage production.

In the context of the sensitivity analysis, the farm-model captures the performance of the system when conditions change. These conditions differ within systems and time, adding uncertainty to the results. The model simulates farmers' decisions on production and management activities in response to changing conditions. The sensitivity analysis points to the prices of beef and male calves as influential parameters for the sustainability performance. Within the framework proposed, higher prices tend to impact the systems through adjustments in the activities as well as in allocation factors, which are estimated based on economic criteria. In view of the lack of agreement on the allocation method (e.g. Wilfart et al., 2021), economic allocation is preferred here over physical allocation, because the two major co-products obtained (meat and milk) have two very distinct markets with stable demand for both, while prices are highly variable. FarmDyn captures country-specific, detailed prices and economic flows, hence offering advantages to carry out consistent economic allocation, relative to conventional LCA approaches. Furthermore, physical allocation is not established for suckler cows because their milk is only used for weaning and yields are unknown (Kyttä et al., 2022).

Finally, the study contributes to the debate on meat production and consumption in the EU, considering multiple dimensions of sustainability. Despite declining consumption of beef meat in the EU, production will likely not vanish (Hocquette et al., 2018). Levers to improve the sustainability of existing production systems, according to the results, could be the efficient usage of feedstuff non-edible by humans, e.g. industry by-products and grasslands and the integration of dairy and beef production (van Selm et al., 2021). Decision-makers should be aware of farm heterogeneity and the possibility of trade-offs between sustainability dimensions. Multi-criteria decision-making (MCDM) tools offer the possibility to combine indicators in a single score and choose options "close to the optimum" using subjective weights (Saeidi et al., 2022). However, the goal of this study is to compare the systems' performance and identify tradeoffs and hotspots in each system among sustainability dimensions and not to rank systems. Performing MCDM analysis would arguably come at the cost of losing detail and complexity and can result in misleading conclusions.

2.5 Conclusion

The model FarmDyn is used to carry out a LCSA of three bull-beef production systems in major producing EU countries including a comprehensive sensitivity analysis. Potential trade-offs between different dimensions of sustainability are identified underlining the need to consider economic and social indicators when comparing the sustainability of beef production. The dairy-based bull fattening system shows better results in environmental indicators while economic profitability, social indicators favoured the systems which utilized grasslands and industry by-products in feeding. FarmDyn enabled the inclusion of price effects in the sensitivity analysis and the economic allocation. Additional indicators would be needed to better represent the social dimension of beef production, although this entails methodological challenges mainly related to data availability. Future research should focus on the application to a larger farm sample to estimate the extent of the observed findings and gain more representative results. The application of MCDM could combine the indicators in a single score and help identifying favourable systems.

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Chapter 3
Exploring Rotational Grazing and Crossbreeding as Options for Beef Production to Reduce GHG Emissions and Feed-Food Competition through Farm-Level Bio-Economic Modeling[1]

Abstract.

In the context of a growing population, beef production is expected to reduce its consumption of human-edible food and its contribution to global warming. We hypothesize that implementing the innovations of fast rotational grazing and redesigning existing production systems using crossbreeding and sexing may reduce these impacts. In this research, the bio-economic model FarmDyn is used to assess the impact of such innovations on farm profit, workload, global warming potential, and feed-food competition. The innovations are tested in a Belgian system composed of a Belgian Blue breeder and a fattener farm, another system where calves raised in a French suckler cow farm are fattened in a farm in Italy, and third, a German dairy farm that fattens its male calves. The practice of fast rotational grazing with a herd of dairy-to-beef crossbred males is found to have the best potential for greenhouse gas reduction and a reduction of the use of human-edible food when by-products are available. Crossbreeding

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with early-maturing beef breeds shows a suitable potential to produce grass-based beef with little feed-food competition if the stocking rate considers the grassland yield potential. The results motivate field trials in order to validate the findings.

Keywords: *beef; climate change mitigation; feed-food competition; innovations; fast rotational grazing; crossbreeding*

3.1 Introduction

Cattle, as ruminants, may contribute to food security through the conversion of feedstuff non-edible by humans into high-quality food [1]. However, in recent years, the sustainability of cattle production has been questioned due to adverse effects, such as its contribution to global warming and the enhanced use of feeds potentially eligible for direct human consumption [2]. The production of 1 kg of protein from milk and meat from cattle uses, on average, 0.7 kg of edible protein and results in emissions of 28–640 kg CO_2eq of greenhouse gases [3]. The reduction of the competition between feed and food production is part of the transition toward more sustainable agriculture, addressing multiple impacts [2,4–6].

With 76 million cattle in Europe in 2021, the sector generated a production value of 82 billion EUR. Near half of these cattle is located in France (22%), Germany (15%), Italy (8%), and Belgium (3%) [7]. Given the economic importance of the sector and its contribution to climate change, innovations are needed to adapt production toward a reduced impact on the environment [8].

In this context, the SustainBeef project, gathering teams in Belgium, France, Germany, Ireland, and Italy, aimed to co-define and evaluate sustainable beef farming systems based on resources non-edible by humans. Several innovations to increase the cattle sectors sustainability have been identified using literature review and focus group interviews in Belgium, France and Italy [9]. Two innovations were identified by farmers and advisors as particularly relevant to improve the use of grasslands: fast rotational grazing (FRG) practices [10] and crossbreeding [11,12]. In rotational grazing, pastures are divided into small paddocks, and the herd occupies one paddock for three to five days before being moved to the next paddock in a predefined order [10]. In

FRG, the residency time is decreased to 0.5 to 3 days. The benefit of such a fast rotation is a higher grass quantity and quality compared to the more common continuous grazing due to a better composition of forage by less selection [13].

Crossbreeding refers to crossing two breeds benefiting from the heterosis effect [14]. Crossbreeding can produce cattle with higher roughage intake capacity, adapted to raw fodder valorization and higher growth rates, as well as better meat quality. While in Ireland, most of the beef cattle are crossbred [15], in France and Belgium, suckler beef breeds are mainly late-maturing animals with high muscle development needing high amounts of concentrates to reach the right fat grade at slaughter [14].

Several studies have addressed both innovations with different breeds and regional settings (e.g., [5,16]). A combined analysis and the possible inclusion in existing production systems is, to our knowledge, under-researched.

Mathematical programming models are a common approach to investigating the impact of innovations at the farm level and assessing the sustainability of agricultural production (e.g.,[17]). Models at the farm scale, such as the FarmDyn model, focus on analysis at the farm level and are frequently used for assessing environmental and economic impacts [18]. The focus on the farm level as the key decision-making unit allows for capturing the impacts of management scenarios and farmers' adaptation to changing conditions [19,20]. The advantages of optimization models can also be used in large-scale sensitivity analysis, which is important in light of high biological variability in key factor assumptions [21,22].

In this study, we use FarmDyn to assess the impact of the introduction of FRG and crossbreeding in typical European beef production systems on their contribution to climate change, protein production efficiency, work time, and farm profit [3]. To account for the high biological variability, a sensitivity analysis is performed to test the impact of key assumptions on the results. The goal is to inform farmers and policymakers about the bottlenecks and benefits of the inclusion of FRG and crossbreeding in order to increase the sustainability of current production systems.

3.2 Material and Method

The analysis is performed from cradle to farm gate based on data from one year (2017), covering representative farms from Belgium, France, Italy, and Germany. The identification and gathering of farm data was part of the SustainBeef project [6]. The farms are also used in [6] and [23] and are considered to be typical farms in major production regions.

3.2.1 *The Three Beef Production Systems*

Three systems are tested in two scenarios compared to a baseline. Key characteristics of the three baseline systems and the included farms in each system are summarized in Table 3.1.

System	**BE**		**FR-IT**		**GE**
Farm [a]	BE-B	BE-F	FR-IT-B	FR-IT-F	GE
Country	Belgium		France	Italy	Germany
Location	Wallonia		Massif Central	Veneto	North-Rhine-Westphalia
No. males sold per year [b]	78	120	38	227	56
No. of cows	155	-	79	-	130
Beef output (estimated carcass weight)	40,379	57,960	16,517	64,864	36,113
Breed	Belgian Blue		Charolais and Salers		Holstein
Arable land	54 ha	-	-	33 ha	198 ha
Grassland	64 ha	-	96 ha	-	27 ha
Other activities	Cash-crop production	-	-	-	Dairy and cash-crop productions

Table 3.1 Overview of the baseline beef production systems [6]. [a] ”B” and “F” stand for breeder and fattener. [b] for breeding farms, this is the number of male calves sold, for fattening farms this is the number of slaughtered bulls.

- The first system articulates two Belgian (BE) farms. The first one is an integrated crop-livestock farm. It holds a suckler cow herd of the Belgian Blue breed and sells the weaned male offspring, cereals, and sugar beet. The weanlings are transferred to a second farm in the system where they are fattened indoors using maize silage and concentrates as feed;
- The second system starts on a suckler cow farm located in the Massif Central, France (FR-IT-B). The farm keeps a herd of Charolais and Salers cows. The herd valorizes pastures during the summer and is kept indoors during the winter. The weaned calves are shipped to a second farm in Italy, where they are fattened indoors using maize silage and concentrates for feeding;
- The third farm is an integrated crop-dairy farm fattening its own male offspring of the Holstein breed. The animals are fattened indoors using maize silage and concentrates as feed. Besides cattle production, the farm is also involved in cash-crop production (cereals and sugar beet).

3.2.2 *Scenarios*

An overview of the scenario design and affected farms is given in Figure 3.1. Three systems consisting of the five farms are tested in two scenarios and compared to a baseline.

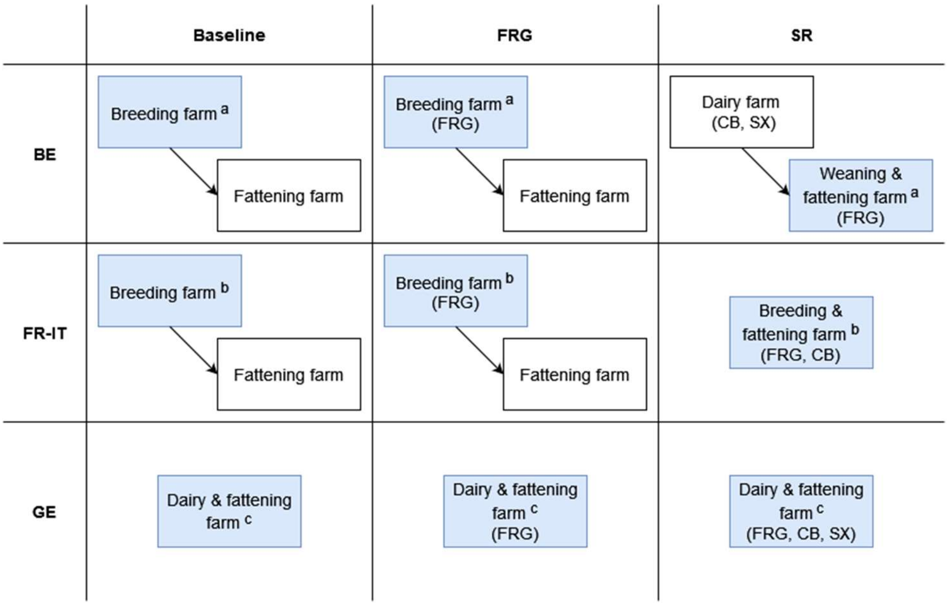

Figure 3.1 Overview of the beef production system considered in the study and the associated scenarios (baseline, fast rotational grazing (FRG), and system redesign (SR)). In the SR scenario, cross-breeding (CB) and sexing (SX) are applied in dairy farms. The farms of interest, labeled a in Belgium, b in France, and c in Germany (in blue), is the farm in which the tested innovation take place. Farm-level indicators, such as the profit, are computed for this particular farm.

In the first scenario (FRG), the farms having grasslands can manage these with fast rotational grazing. Fast rotational grazing refers to cattle periodically being moved among paddocks as opposed to continuous grazing, where a single plot is grazed for the entire season. Previous studies have found that FRG can improve the quantity and the quality of the grazed grass [24]. The increase in yield is due to a more evenly grazed sward, and an optimal balance of regrowth and grazing to offer fresh grass with high nutritive value. FRG therefore has consistently higher forage yield with a comparable yield distribution [25]. The choice of applying FRG, the area of grassland impacted and the cattle type to which it is applied results from the economic optimization performed with the model and are not defined a priori.

The affected farms are the breeding farms in BE and FR-IT and the dairy herd on the farm in GE. Due to the lack of data on actual FRG on the case study farms, possible yield distributions have been derived based on the yield distribution from grazing observed in the baseline with the help of field experts. The FRG has also been discussed and validated in focus group interviews with farmers [9]. The approach was chosen to ensure that yields reflect conditions faced by farmers and not laboratory conditions.

The resulting monthly dry matter (DM), crude protein (CP), and metabolizable energy (ME) yield for continuously grazed and FRG grazed pastures in each system is depicted in Figure 3.2. The yearly total DM yield of FRG is 9.0 t/ha in BE, 4.4 t/ha in FR, and 9.9 t/ha in GE compared to 8.0, 4.0, and 9.0 t/ha, respectively, in the baseline. The total crude protein yield per year of FRG is 1.9, 0.9, and 2.1 t/ha in BE, FR-IT, and GE, respectively. The grazing period and yield distribution is determined by local pedo-climatic conditions with FR-IT having the lowest yield due to the mountainous climate and poor soils. Supplementary feed on pastures is optional for the model to meet the animals' nutrient requirements. The practice is bound to higher work time requirements and costs due to extra fencing and herding. The work time for pasturing increases by 10%, and the variable costs increase by EUR 37.5/ha compared to continuous grazing.

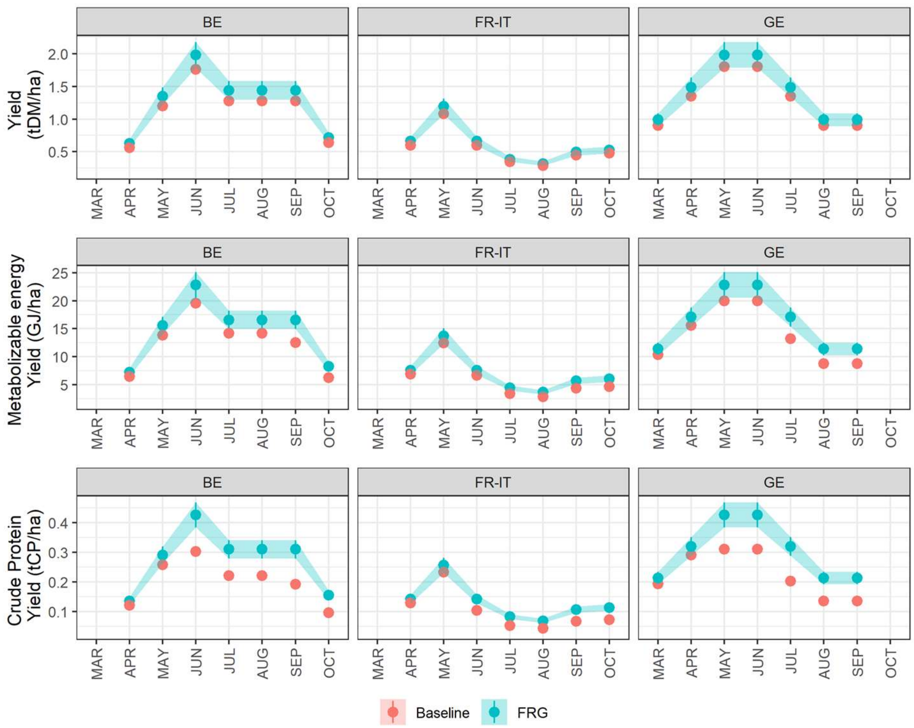

Figure 3.2 Dry matter, metabolizable energy and crude protein yield profiles for continuously (CG) and rotationally grazed (FRG) pastures in the three production systems.

The second scenario redesigns the systems (SR) to promote the transition toward more sustainability. The scenarios are designed by combining crossbreeding and FRG considering local conditions. Field experts and focus group interviews with advisors and farmers initialized the scenarios. The possibility to use FRG is carried over from scenario 1.

- In the BE system, the fattening farm is removed from the system while the breeding farm in the system is transformed into a growing-fattening farm. A dairy farm is added to the system to supply male calves entering the growing-fattening farm. The dairy farm keeps a herd of 70 cows of the Holstein breed. For the renewal, some cows are inseminated with female Holstein-sexed semen while others are inseminated with male-sexed semen of the Belgian Blue breed. The calves enter the growing-fattening farm when 3 weeks old at the cost of EUR 200. They are raised and fattened on grasslands and repurposed stables of the initial suckler cow enterprise. The bulls are grazing from April to October. Based on the performances observed by [11,26], the bulls are sold when 19 months old with a carcass weight of 330 kg (carcass yield 55%), a conformation score of U-R, and a fat score of 2–3. A price of EUR 3.4/kg carcass was therefore considered based on the official Belgian prices [27];
- In the redesigned scenario of the FR system, the fattening farm in Italy is removed from the system, and the finishing period is happening at the French breeding farm. Furthermore, the Charolais breed cows are inseminated with the Angus breed. The Angus breed is known for its ability to valorize grass resources and the high fatness score of its meat [28], resulting in higher selling prices. The bulls are slaughtered when 14-month-old at a carcass weight of 300 kg with a price premium of EUR 0.4 per kg carcass weight, adding up to a total price of EUR 4.18/kg carcass;
- In the German redesigned scenario, the farm uses crossbreeding and sexed semen to reduce the number of breeding heifers to the herd renewal needs and produce high-yielding Belgian Blue by Holstein crossbred male calves. The calves are fattened at the farm and sold at the age of 21 months at a carcass weight of 413 kg and a price of EUR 3.8/kg carcass.

3.2.3 *Overview of the FarmDyn Model*

The FarmDyn model has been used for sustainability assessments in the context of European cattle farming before (e.g., [22,23,29]). Here the model is used to analyze each farm in each scenario, over the period of one year. FarmDyn is a bio-economic single-farm optimization model [30]. The model maximizes farm profits by optimizing agricultural activities subject to boundary conditions given by farm endowments, prices, legal restrictions and policies, and available technology.

Farm activities include farmers' decisions: the type and quantity of livestock to keep, their feeding, the crops cultivated and the fertilization associated. Herd demographics including calf birth, raising, replacement, slaughter, and selling are captured monthly. The methodology of the feed planning tool Zifo2 [31] is used to estimate the animals feed requirements, by considering animal performance and lactation periods balancing the needs for dry matter, fiber, protein, energy, and nutrient intake. Feeding can be performed by a variety of bought and self-produced feedstuff described in [32].

The cropping activities are scenario and farm-specific with regional yields and land endowments. Arable crops are divided into cash crops (wheat, barley, rapeseed, sugar beet) and fodder crops (maize silage and catch crops).

Grassland production options consider different forms of harvest (silage and hay in bales or pit and grazing) and different cuts differentiated by seasonality, productivity, and quality of the harvest. The fertilizer needs of crops and grassland are calculated by the model by considering the total nutrient removal in the form of harvested products, nutrients delivered from soil and air, and leached and gaseous nutrient losses. The fertilizer need can be met by manure, excreta from grazing animals, and mineral fertilizer.

Manure is handled as solid (BE, FR-IT) or as liquid manure (GE). Manure is reused for crops and grassland fertilization within the farm. In dairy herds, milk is considered, for the analysis, as a by-product. Economic allocation is applied to allocate the impacts between the production of milk and beef. It is the preferred method for allocation because the necessary information on prices and economic flows is readily available to be used in the modeling framework. When available, the prices are taken from the farm data. Where no exogenous market price exists, the optimization model is used to provide the shadow price (The shadow price refers to the opportunity costs and are derived as a marginal value in the optimization process) for the economic allocation [33].

3.2.4 *Sustainability Indicators*

The systems' contribution to greenhouse gas (GHG) emissions, the work time (WT) invested in production, farm profit, and the human-edible protein production efficiency (HEP) are calculated as sustainability indicators. A Life Cycle Assessment approach similar to [23] is used for GHG emissions and WT.

The system boundaries, as depicted in Figure 3.3, to calculate these indicators include all the processes, from cradle to the farm gate, necessary to deliver 1 kg of beef carcass, considering culled cows, heifers, and bulls. This constitutes the functional unit in which the WT and GHG emissions are expressed in each system.

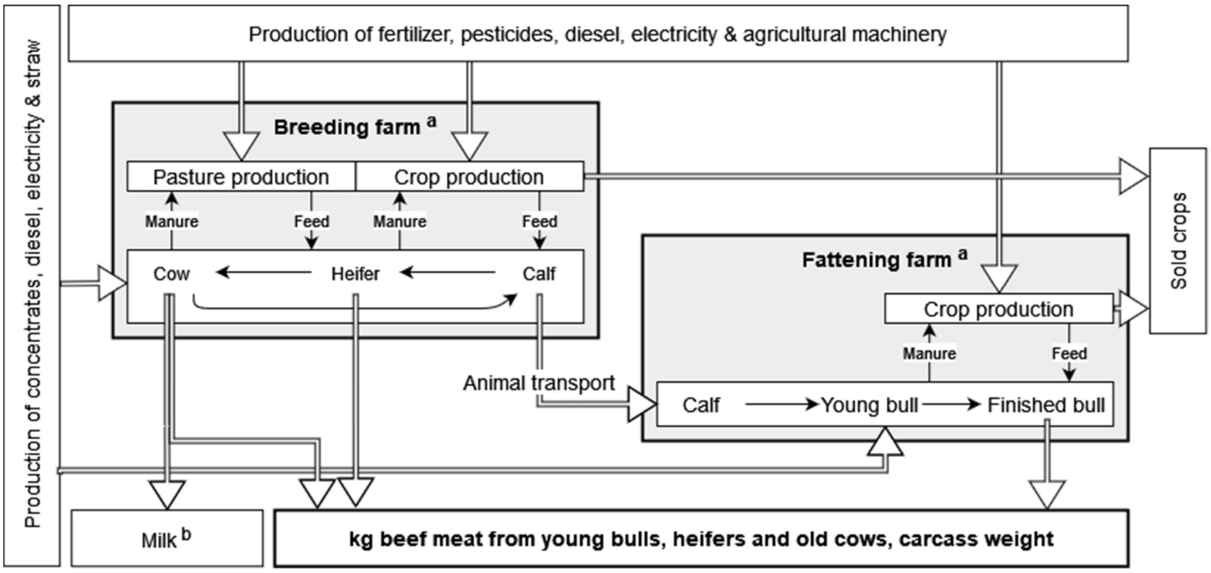

Figure 3.3 System boundaries of the analyzed beef production systems. Source: adapted from [23]. a in the German system breeding and fattening are integrated in one farm sparing animal transport. b milk is considered a co-product on the dairy farm of the German system and in the system redesign scenario in Belgium.

Included processes are crop production for feeding with the substages cultivation, seeding, fertilizing, pesticide application, liming, and harvest, herd management including caretaking of cows, heifers, and calves, fattening, and transport of animals from one farm to another in the French–Italian and the Belgian systems.

Agricultural inputs and services are included within the system boundaries, i.e., machinery production and operation, energy, concentrate, fertilizer, and pesticide productions.

Estimated GHG emissions include methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The methodology used and considered sources to quantify on-farm emissions are from Table A1 in the appendix. Emissions arising from the provision and transport of major externally bought inputs and services, namely feedstuff, bedding material, fertilizers, pesticides, diesel and agricultural machinery provision and operation, are taken from the Ecoinvent database version 3.6 [34]. GHG emissions are characterized using the global warming potential (GWP) in kg CO_2eq. with the ReCiPe methodology at the midpoint level (hierarchist perspective) [35].

The WT indicator considers the time taken for herd feeding and caretaking, calving, fieldwork allocated to beef production, stable maintenance, fertilization, management, and administrative work.

Farm profit is calculated considering the following costs and revenue streams: revenues from sold beef (old cows, heifers, bulls), sold milk, sold calves and cash crops, subsidies (coupled and decoupled support), and costs from animal replacement, calf rearing, costs of bought feed, costs of fertilizers, phytosanitary products, diesel purchases, variable machine costs (maintenance and operation), other variable costs (veterinary interventions, crop insurance, etc.) and depreciation of basic structures (sheds, silos) and machinery (tractors and applications). Data on prices and work time requirements of different tasks have been collected in the respective farms. Missing data on prices and work time was complemented from [36]. The profit is computed at the farm level, in the farm implementing the innovate practice: the breeder farm in BE and FR-IT and the dairy farm in GE.

The net HEP efficiency is calculated as the share of human-consumable protein produced in the form of beef meat divided by the amount of human-consumable protein in fodder fed used to produce beef meat. The human-consumable share of protein and calorie content of the feedstuff and meat is based on Laisse et al. [5], Ertl et al. [4], and Wilkinson [37]. The indicators represent the contribution of beef production to human nutrition [6]. In the beef production systems, where breeding and fattening happen in different farms, impacts of beef meat produced in the breeding farms are calculated per kg of transferred animals, which are subsequently implemented as emission factors into the optimization problem of the fattening farm in order to assess the whole system's performance.

3.2.5 *Sensitivity Analysis*

The sensitivity of results to key assumptions on parameter values is tested in a global all-at-once sensitivity analysis. This includes the capacity of sheds to contain animals, the yield of grasslands utilized for FRG, and the age at which the bulls are slaughtered. Parameter values vary by ± 20% for the stable size and by 10% for grasslands yields in FRG and for the age at which the bulls are slaughtered from the median scenario. Using Latin Hypercube Sampling, a sample of 100 draws with simultaneously changed levels of the parameters is created, covering the full range of possible factor level permutations. Uniform distributions without correlations are assumed. For each draw and each farm, the profit optimization is run again, considering the changed parameters. The results of each optimized farm are combined in a single data frame for each system. GWP, net HEP efficiency, WT, and the farm of interest profit in each scenario are compared to the baseline. The net HEP efficiency is then studied as a function of the stocking rate, defined as the livestock unit (LU) per ha of permanent grasslands, as the other surfaces resources could potentially produce human-edible food.

3.3 **Results**

3.3.1 *FRG Scenarios*

The effect of FRG on GWP is marginal (< ±2%), whatever the system (Figure 3.4 and Figure 3.5). The better nutritive value of the FRG swards reduces methane emissions from enteric fermentation (−6% in BE). However, emissions related to grassland and crop management (+10% in BE) are higher because of the higher fertilization, including through animal dejections, required to support the higher quality and quantity yield of FRG.

In the BE case, the GWP improves by 1% (−0.3 kg CO_2eq/kg beef) compared to the baseline. The additional yield from FRG reduces the area of maize needed for feed production. The profit is increased (+5%) thanks to the freed-up land that is used for cash-crop production (wheat, sugar beet). The impact of innovation on farm input/output is summarized in Table A2 in the appendix. The introduction of FRG increases working time to produce 1 kg of carcass by 17.5% (1.10 min per kg carcass) compared to the baseline. The net HEP efficiency in BE in the FRG scenario is 0.69. This is a slight increase of 3% compared to the baseline related to the substitution of maize silage and concentrates, including protein that could be used for human nutrition, by grazed grass. For both the baseline and the BE-FRG, the sensitivity analysis shows a net efficiency negatively correlated with the stocking rate in the breeder farm and increased further under 3 LU/ha of permanent grassland (Figure 3.6).

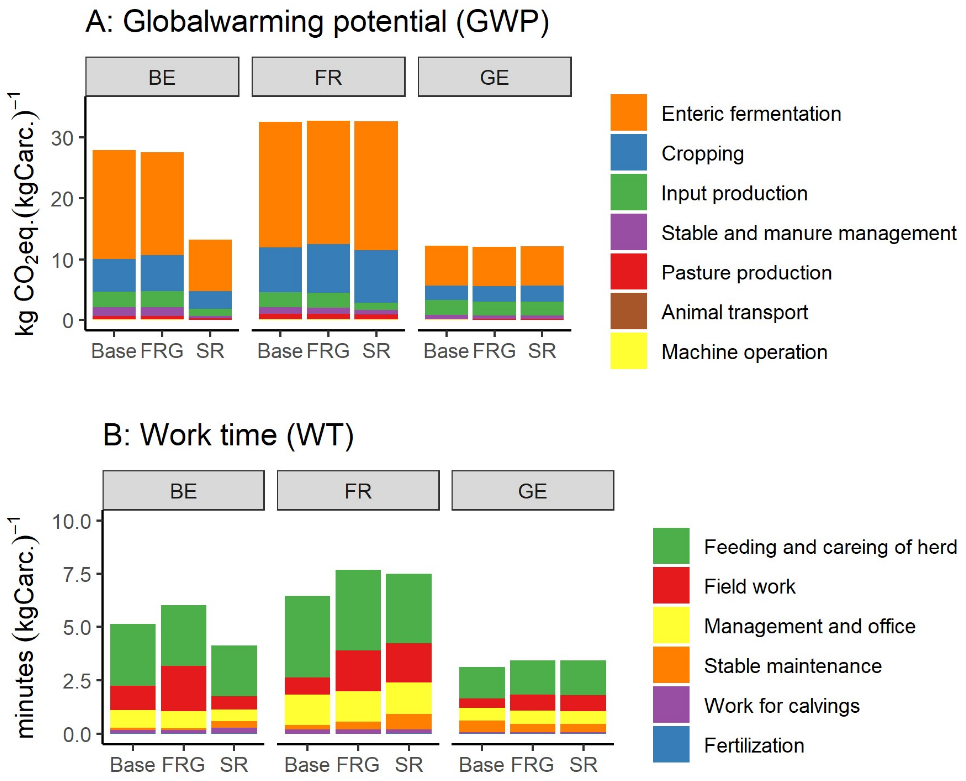

Figure 3.4 A) GWP per kg of carcass and its different sources for the baseline (Base) and in the fast rotational grazing (FRG) and system redesign (SR) scenarios applied to the Belgian (BE), French–Italian (FR-IT), and German (GE) case studies. (B) Work time per kg of carcass and its different components.

In the FR-IT case, the higher emissions from fertilizer application outweigh savings in enteric fermentation resulting in a slightly higher GWP compared to the baseline (+0.6%, +0.2 kg CO_2eq/kg beef). The introduction of FRG management improves farm profitability in comparison to the reference scenario (+4%). The invested time to produce a 1 kg carcass increased by 18.9% (1.22 min). The net HEP efficiency improves by 4.5%, which results in an indicator value of 0.6. The sensitivity analysis reveals that the net HEP is limited at 0.6 for a stocking rate under 1.1 and drops for a higher stocking rate (Figure 3.6**)**.

In the GE case, the FRG is mainly used for dairy stock. The innovation has, therefore, a limited effect on beef production. The farm profit increased by 2.5%. The GWP is reduced by 1.6% (−0.2 kg CO_2eq/ kg beef) compared to the baseline. Besides the effects observed in the BE and

FR-IT cases, the additional yield in the GE case is used to replace bought concentrates that bare a high emission load from production. The work time to produce 1 kg of carcass is increased by 9.5% (0.3 min), and the net HEP efficiency is slightly reduced by (−0.4%). The sensitivity analysis shows no significant dependence on the stocking rate (Figure 3.6).

3.3.2 *SR Scenarios*

In the BE-SR scenarios, the farm of interest profit is improved by EUR 48,000 (+28%). While the production cost is increased by EUR 67k, which mainly includes the costs of the crossbred veal and additional feed (pressed sugar beet pulp) costs, the subsidies are reduced by EUR 17k, corresponding to the coupled subsidies associated with the suckling cows of BE-base. The revenues are increased by EUR 84k for beef and EUR 45k for crops. The quantity of beef produced is about 83,691 kg carcass for a stable of 300 bulls per year, which is twice the baseline situation and contains only finished meat. At the system level, the GHG emission per kg of carcass produced is reduced to 13.2 kg CO_2eq/kg carcass (−52%). The net HEP efficiency is increased (Figure 3.5) and negatively correlated to the stocking rate according to the sensitivity analysis (Figure 3.6). Values above one are obtained thanks to the stable size considered, the use of grass, and bought by-products for the bulls' fattening.

In the FR-IT-SR system, the redesign requires keeping animals longer on the breeding farm, evolving toward a breeding and fattening farm. As each animal requires more feed, fewer cows and bulls are produced compared to the baseline system, but more beef carcass is produced (19,317 kg carcass (+17%) of finished meat, in the median run), leading to higher beef revenues (+14%) and profit (+20%). Considering the whole production cycle with the initial Italian fattening farm, this redesigned system maintains (−0.5%) the global warming potential of beef meat. The sensitivity analysis shows that its net HEP efficiency is negatively correlated with the stocking rate, and a stocking rate lower than 1.1 enable a protein net efficiency higher than 1. This system is less labor efficient relative to the baseline situation but more labor efficient than in the FRG scenario.

In the GE-SR case, the crossed bulls tend to be more profitable (+1.5%) and have nearly no influence on climate change (−1%) as they have a higher live weight gain and carcass yield.

Due to the use of sexed semen, the number of bulls fattened is higher, which globally increases beef production to 40,629 kg carcass (+13%). This leads, compared to the initial scenario, to an increase in the demand for protein feed. The additional animals fattened and the higher protein demand for fattening lead to an extension of fodder production on arable land, i.e., maize silage, and a higher import of protein-rich concentrates. Therefore, the net HEP efficiency declines to 0.4 (−20%), as more forage comes from feed that is in competition with humans with no stocking rate dependence, as for the FRG scenario.

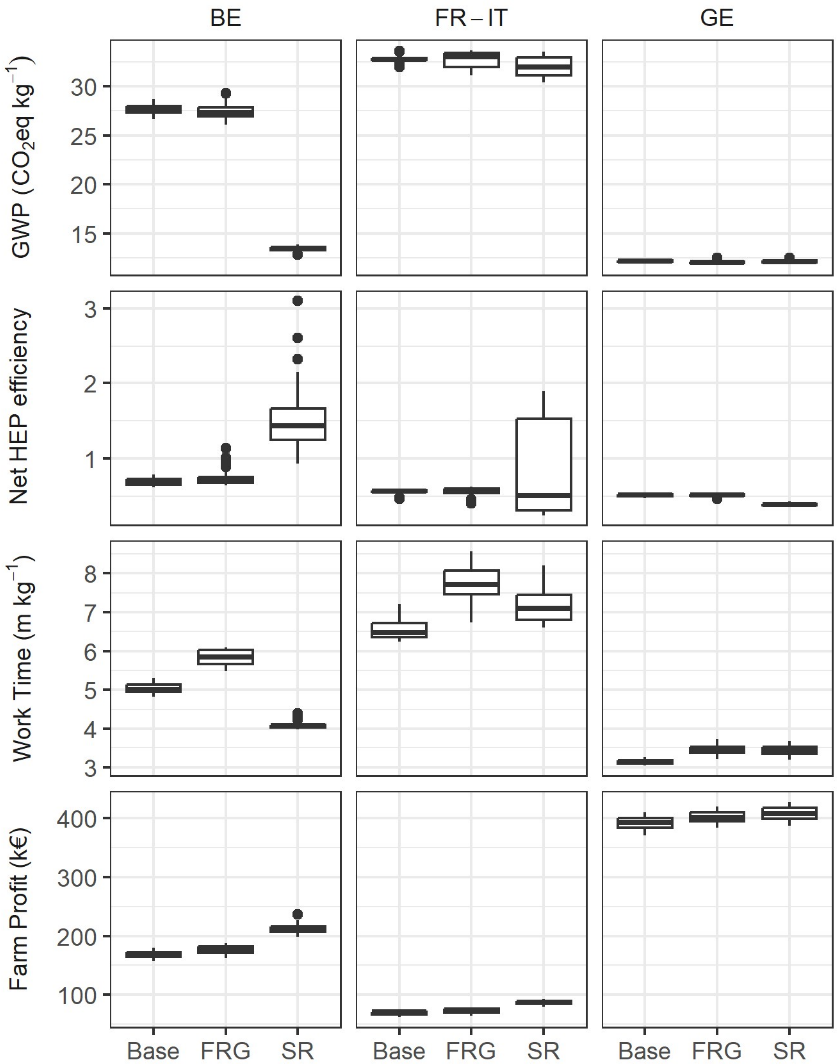

Figure 3.5 Results of sustainability evaluation of the scenarios supported by the sensitivity analysis for the baseline (Base) and the fast rotational grazing (FRG) and system redesign (SR)

scenarios applied to the Belgian (BE), French–Italian (FR-IT), and German (GE) case studies. The variables studied are from top to bottom: the global warming potential for the production of 1 kg of beef carcass, the net human-edible protein efficiency, the work time to produce 1 kg of beef carcass, and the farm profit.

Figure 3.6 Relation between the net efficiency of HEP production and the stocking rate in livestock unit (LU) per ha of permanent grassland (PG) in the farm of interest for the tested scenarios for the baseline (Base) and in the fast rotational grazing (FRG) and system redesign (SR) scenarios applied to the Belgian (BE), French–Italian (FR-IT), and German (GE) case studies.

3.4 Discussion

3.4.1 *Fast Rotational Grazing*

Defining baseline grazing practices in Belgium, Germany, and France in beef production is difficult due to the diversity of the grazing management schemes implemented and the lack of available literature relating to the impact of grazing management on forage yields, both in quantity and quality, in commercial farms. The qualities considered in our study are lower than those found in [38] in July–October and are, therefore, potentially pessimistic compared to current farmer practices.

Still, at the farm level, the main impact of FRG is an increase in work time due to the increase in the workload related to pasture management. Since pasture complementation is possible and performed, no significant time reduction is observed for feeding. Nevertheless, this supplementation depends on farmer objectives, and some testimonials state that working comfort is improved thanks to reduced time spent indoors for animal management [22,25]. The second effect is the reduction of tillable land used for feed production, resulting in higher cash-crop production and, therefore, profit. While expected, this observation deserves further investigation in regions where droughts have become more frequent in the last years, leading to the use of more conserved fodder. Indeed, only a global grass yield uncertainty has been included in the sensitivity analysis, but no strong grass growth limitation is sometimes observed under extreme drought periods.

Applying the FRG to breeder farms only shows globally a limited impact at the system level. Indeed, the net HEP efficiency evolution is limited by the use of feed in competition with humans during the fattening process. Concerning enteric methane emission in this scenario, while the effect of an increase in grass quality on cattle ingestion is taken into account, the potential reduction in methane production rate is not considered in this study since we found no coherent Tier-3 methodology that could account for this effect. This effect deserves further exploration.

Since fertilization is computed based on nutrient removal, increasing grass production with FRG will increase fertilization needs. These needs are partially fulfilled by the increase in excreta from grazing animals. This methodology offers a consistent framework but needs refinement to take into account indirect effects, such as the impact of FRG on white clover or other grassland species.

3.4.2 *System Redesign*

Two types of crossbreeding have been tested in this study to produce beef: crossing a continental beef breed with an early-maturing breed [14] and crossing a dairy breed with a Belgian Blue sire [22].

The Salers-Angus crossbreeding has been tested in the INRAe experimental farm of Laqueuille [12]. Crossbreeding a Salers cow with an Angus bull produces grass-fed young fattened animals. However, more harvested forages were required per animal since young bulls were kept one additional winter on the farm. This explains that high net HEP efficiency is obtained only for reduced herd size (Figure 3.6), allowing to interconnect animal needs to grassland resource availability. In addition to the FRG, when grazing is possible, the quality of the fodder harvested and stored must always be excellent to obtain sufficiently heavy and well-conformed animals. It was a challenge for the past years characterized by severe drought limiting forage self-sufficiency in the experimental farm. Furthermore, as this type of animal is far from the standards in the beef industry, the marketing of animal products was not always favorable. In fact, there have been instances where finished animals have been sold for less than if they were sold in foreign markets. The implementation of such system redesign does not only lead to modifications during the production phase but to modifications on the whole value chain up to the consumers, with a need to overcome some lock-ins at different levels [39]. While crossbreeding with an Anglo-Saxon breed was considered in this study, the potential of using early-maturing phenotypes within local breeds could be a lever to promote the adoption and the valorization of grass-based beef production.

The production of beef from the dairy herd offers the possibility to strongly reduce GHG emissions thanks to the low CO_2 costs of the crossbred calves coming from the dairy herd, as keeping the mother cows is the dominant contribution to all impact in the suckler-based system [40]. Indeed, while having similar or even higher daily methane emissions than suckler cows, dairy cows produce high quantities of milk, which dilutes the GWP of the male calves produced. Pasture-based dairy-beef systems have also been studied in [16], where similar GHG emissions from 11 to 17.2 kg CO_2eq/kg carcass are computed for the progeny of late maturing sires, depending on the slaughter age and the soil quality. The important change in the BE-SR scenario and the choice to keep a similar stable size, and therefore a limited stocking rate after the redesign, mainly explain the suitable net HEP efficiency. Indeed, this stocking rate allows the production of grass and by-product-based meat with a low dependency on feed resources that could be valorized by humans. In [16], high net HEP efficiencies are observed only for older steers slaughtered at 28 months. Nevertheless, these steers have the highest GWP. In the BE-SR scenario, the grass and by-product-based bull system tested, with bulls slaughtered when 19 months, allows for combining lower GHG emissions and lower feed-food competition. Now, the possibility of achieving a sufficient fat score under such a production scheme with bulls requires experimental validation. Indeed, in [41], in Ireland, while crossbred steers with Belgian Blue obtained heavier carcasses with better conformation than Friesian or Aberdeen Angus crossbred, their carcasses were not acceptably finished off pasture at 19–20 months with rotational grazing. The possibility of using early-maturing sires could facilitate the fattening, with the drawback of a higher GHG emission per kg of carcass [16]. Adding a three-month period of fattening in the barn after the pasture, as studied in [11], showed acceptably finished carcasses, heavier than considered in this study. The German scenario, in which a reduced net HEP efficiency is observed, indicates potential drawbacks of the adoption of this new technology on the dairy farm without reducing the stocking rate in order to maintain the level of fodder autonomy.

The stocking rate range allowing for high net HEP efficiency is different in the BE (<2.8 LU/ha PG) and FR-IT (<1.1 LU/ha PG) system redesign (Figure 6). This difference could be explained by the availability of by-products, and the higher grasslands yield observed in Wallonia compared to the Massif Central [42]. This threshold is not reached in the German case, where 88% of the agricultural area is composed of tillable land leading to a high stocking rate per ha of grassland and, therefore, to the inclusion of a high share of human-edible protein in the beef diet.

While an important reduction of GHG emissions is observed per kg of carcass beef produced in the BE-SR scenario, the results do not transfer to farm-level emission since beef production per hectare has also doubled. As in the model, methane emissions are computed based on feed ingestion, which is similar between the baseline and the SR in the Belgian scenario. Such an innovation would only be beneficial to reduce GHG at the territorial level if it is associated with a reduction of the land used for beef production.

3.4.3 *Relevance of the Modeling Framework to Redesign Production Systems*

The modeling framework allows having a sustainability assessment related to innovation implementation. The number of indicators presented and discussed here has been limited to net HEP efficiency for feed-food competition and GWP for the environmental pillar of sustainability. The scope of the sustainability evaluation could also be enlarged while taking into account impacts such as acidification or eutrophication, as was performed in [23]. Increasing the number of indicators, as in [6], for instance, could improve the understanding of the impact of innovation at different scales.

While the quality of the output depends on the quality and the details of the assumption made in the modeling, some uncertainties remain as the ability to produce a carcass with a decent fat score in the BE-SR scenario. Those uncertainties are meant to be further explored during focus group discussions with farmers and other stakeholders, during which the current results are used as a base for discussion.

In this study, the impact on the Belgian or on the Italian fattening farms is not explored. Similarly, a generalization of the fattening of dairy crossbred bulls will have an impact on veal production in the EU. Widening the scope of the study is, therefore, necessary to provide a complete picture of the impact of such a redesign.

3.5 **Conclusion**

Using the farm-model FarmDyn innovations were tested on their contribution to the net HEP efficiency, GHG emissions, the work time necessary for production, and the farm profit. The introduction of FRG increased farm profit and work time. FRG associated with crossbreeding with early-maturing breeds and subsequent fattening on grasslands increases net HEP efficiency compared to intensive fattening of weanlings with maize silage, as observed in a French–Italian system. However, the effect is limited when connected to high stocking densities needing the importation of huge amounts of external feeds. Beef production based on dairy herds allows for significantly reduced GHG emissions compared to traditional suckler cow systems in the

Belgian system tested. Nevertheless, a net protein efficiency higher than one also requires a stocking rate adapted to grassland production and the availability of by-products.

The results show potential pathways to improve the sustainability of current beef production systems at the farm level. Future research should focus on experiments with larger farm samples to validate the results given the high degree of variability found in beef production systems within each country and ultimately verify results in field trials on current farms.

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Chapter 4
Greenhouse gas abatement costs of Norwegian dairy farms

Abstract
The Norwegian Government agreed with the two leading farmers' unions to include the agricultural sector in the national effort to mitigate greenhouse gas (GHG) emissions. The parties agreed to abate 5 million t CO_2eq in 2021-2030. Emissions shall be mitigated by reducing food waste, dietary change, and farm-level abatement measures. Among these, the farmers' unions agreed to pursue mitigation efforts at the farm level. This paper contributes to the current debate by calculating marginal farm-level abatement cost curves of representative Norwegian dairy farms. Dairy farms are chosen due to their contribution to the sectors' emissions. The farm-level optimization model FarmDyn is adapted to Norwegian conditions to represent local prices, yields, endowments, policies, regulations, emission calculation, and abatement technology. The model is applied to seven representative dairy farms based on the Farm Accountancy Data Network (FADN) identified by K-medoid clustering. The results show that up to 5% of farm-level emissions can be mitigated at costs below the carbon tax level proposed by the Norwegian government (2000 NOK per t CO_2eq) on farms with low stocking density. Further mitigation efforts are bound to high costs. The preferred abatement measures are optimising the feed rations of cows towards a higher share of concentrates, replacing regular diesel with biodiesel, and using advanced manure application technology. Once these measures are used to their full potential, farms reduce their herds to abate additional emissions. This happens earlier on farms with a high stocking density due to their

limitations in increasing the share of concentrates. Therefore, dense livestock farms tend to bear higher abatement costs. Due to high farm-level abatement costs, mitigation targets conflict with other goals of the Norwegian agricultural policy, namely securing farm income and maintaining production. Compensation payments could address these trade-offs. Given the limited reduction potential for farm-level abatement at competitive costs and following the intentional agreement, we suggest that dietary change and food waste reduction must achieve a significant share of the envisioned abatement target.

Keywords: *Mitigation, Marginal abatement costs, Dairy, Norway, Global warming potential, Climate policies, Impact assessment*

4.1 Introduction

Norway signed the Paris Agreement in 2015 and bound itself to reducing domestic greenhouse gas (GHG) emissions by at least 50% by 2030 compared to 1990 (United Nations, 2015). The Norwegian agricultural sector emits about 10.1 million t CO_2eq annually and contributes around 10% to the total GHG emissions in Norway (Statistics Norway, 2021). Cattle farming is among Norway's most important agricultural activities, accounting for roughly 50% of Norwegian agricultural land use, value creation, and employment (Mittenzwei, 2018). Furthermore, dairy cows contribute 50% of Norway's agricultural sector's GHG emissions (Mittenzwei & Prestvik, 2022).

Given its substantial contribution to GHG emissions, the agricultural sector is included in the Norwegian national GHG reduction plan (Norwegian Government, 2021). In 2019, the Norwegian Farmers Union and the Norwegian Farmers and Smallholders Union entered into an intentional agreement with the government to reduce GHG emissions from the agricultural sector by 5 million t CO_2eq between 2021-2030 compared to a non-abatement scenario (Norwegian Government, 2019). The intentional agreement covers yearly emissions of 10.5 million t CO_2eq, including emissions reported in the agricultural sector and emissions caused by agricultural fuel and energy use. The agreement consists of two parts. The first contains farm-level mitigation measures for which the farmer organisations are responsible, while the second part covers emission reduction through dietary change and less food waste. The government is accountable for achieving emission cuts for the latter two measures. The agreement has not yet materialised in concrete policies or private enterprise commitments to induce reduction efforts.

Besides GHG abatement, Norway has ambitious policy objectives related to agriculture, such as ensuring food security, maintaining agricultural activity throughout the country, and creating value. This is reflected, amongst others, in high levels of direct payments and high trade barriers (OECD, 2021). GHG policies need to be designed in coherence with these existing policy goals. Furthermore, GHG reduction policies require knowledge of different sectors' cost-effective abatement measures and abatement costs. FÆHN et al. (2020) calculate the costs of abating GHG emissions in Norway's sectors not covered by the EU Emissions Trading Scheme (non-ETS) by 50% by 2030 using a large-scale sector model. They estimate costs of 3,200 and 3,500 NOK per t CO_2eq. However, the study lacks guidance on abatement measures, leaving the agricultural sector out. Bustamante et al. (2014) conclude that mitigation policies must be based on regional findings due to their complexity in specific contexts. Such knowledge is missing for agriculture in Norway.

To fill this gap, we contribute the first marginal abatement cost curves (MACC) for Norwegian dairy farms as the largest emitter within agriculture. MACC relate additional GHG abatement to its costs. This is a common approach to getting information about potential mitigation efforts and identifying cost-effective GHG mitigation options to guide farmers and policy initiatives while integrating the agricultural sector into the national abatement effort (Eory et al., 2018). Regarding policy coherence, MACC shows the costs for farms to mitigate GHG emissions and allow conclusions on farm income if reductions are realised by the 'polluters-pay principle.' Since the Norwegian government also aims to strengthen farm income, such abatement costs can be interpreted as trade-offs between policy goals and justify possible compensations. Finally, insights on the abatement costs at the farm level are crucial to sharing the emission burden based on informed consent between the farm level and consumption change efforts considering the intentional agreement and between the agricultural and other sectors.

Different approaches allow for estimating the MACC of the agricultural sector (see Vermont & De Cara, (2010)). One of these methods is using micro-economic mathematical programming models at the farm level. This method combines the benefits of detailed technology description at the farm level with the inclusion of interaction effects of different measures and their impact on other farm activities. Furthermore, farm-level mathematical programming models can represent heterogeneity between farms, rarely captured in engineering MACCs or sector model approaches (Eory et al., 2018). Unsurprisingly, the method was employed for several European regions and had different scopes of analysis (Lengers et al., 2014; Mosnier et al., 2019).

This research aims to explore abatement options and costs for representative Norwegian dairy farms and subsequently inform stakeholders and decision-makers about possible ways to mitigate GHG emissions at the farm level, associated costs, and policy implications. To do so, we apply the bioeconomic farm model FarmDyn to calculate MACC for a representative selection of farms. The FarmDyn model was initially built by Lengers et al. (2013) to analyse the effects of different GHG indicators on MACC and other drivers for German dairy farms. The model has yet to be employed for Norwegian agriculture, which is unique due to the pedo-climatic conditions with a limited growing season, a heterogeneous farm structure, and substantial policy interference. Therefore, FarmDyn is parametrised and extended for the Norwegian production conditions as part of this research.

4.2 **Materials and Methods**

4.2.1 *Farm data*

The analysis focuses on dairy farms as these comprise the largest share of the agricultural sector's emissions (Statistics Norway, 2021). Defining representative farms instead of assessing the whole sample allows for an in-depth description of the role of production technology, a detailed analysis of results, and the identification of relevant farm characteristics (Chibanda et al., 2020). Norway's Farm Accountancy Data Network (FADN) data is used to derive a sample of 7 dairy farms (NIBIO, 2019) using K-medoid clustering after data-cleansing for faulty data entries to ensure representativeness. Variables used for the cluster analysis and the number of clusters are chosen via a silhouette plot. The resulting representative farms differ by region, size, yield level, and further production branch. The farms are described below, while crucial characteristics are summarised in Table 4.1.

- The farm JÆR represents dairy production in Jæren. The conditions benefit grass production, resulting in a high yield. The farm keeps 40 cows with a high milk yield.
- The farm M&R operates in the largest dairy production region, Møre & Romsdal. It has a herd of 32.8 cows. The farm's grass yield and milk yield are average.
- The farm ØL is in the Østland region. With a herd size of 13.8 cows and a low milk yield, the farm is representative of small, extensive farms in the area.
- The farm VL is representative of a large farm in the Vestland region. It keeps 35 dairy cows with a high milk yield. In addition to dairy production, the farm fattens the male offspring of the dairy cows for beef production.
- The farm NN is in North Norway. Due to the short growing season, grass yields are low. However, the farm compensates for this with a large area of farmed land and larger shares of concentrates to sustain the herd's feed demand. The high share of concentrates in the diet leads to a high milk yield.
- The farm TR.flat is located in the planes in Trondelag county. The region is known for cash crop production. Accordingly, the farm is also endowed with arable land used for cereal production. Due to the good growing conditions, the grass yield is the highest among the analysed farms. The farm keeps 37.2 cows with an average milk yield. The farm also fattens the male offspring of the dairy cows for beef production.

- The farm TR.hill is located on the mountainous outskirts of Trondelag County. It has a herd of 26.5 cows with a lower milk yield. The farm is endowed with medium-yielding grasslands, and the male calves from dairy production are fattened as bulls for beef production.

Farm	JÆR	M&R	ØL	VL	NN	TR.flat	TR.hill
Municipality	1121	1543	513	1426	1871	1702	1638
N. Cows	39.7	27.1	13.5	35.1	34.9	37.2	26.5
N. bulls	-	-	-	14.0	-	10	6.5
Grassland (ha)	29.8	32.8	22.7	53.7	82.4	37.3	53.2
Pastureland (ha)	13.0	2.7	3.2	19.0	7.4	0.8	10.0
Arable land (ha)	-	-	-	-	-	12.8	-
Grass yield (t DM)	4.48	3.58	3.47	3.20	2.39	4.57	3.39
Yield Barley (t)	-	-	-	-	-	5.01	-
Milk yield kg ECM	8061.03	7829.52	6805.56	8139.52	8224.33	7630.03	7139.96
N AWU	1.4	1.63	1.22	1.73	1.71	2.25	1.80

Table 4.1 Overview of the analyzed farms. Own illustration based on data from NIBIO (2019).

4.2.2 *The FarmDyn model*

This study uses the single-farm optimisation model FarmDyn to calculate MACC. FarmDyn simulates farm management and generates the economically optimal farm plan that maximises the farm's net present value. FarmDyn originates from a research project that calculated MACC for

German dairy farms (Lengers et al., 2013) and has been continuously updated and extended in recent years. FarmDyn has been applied to various farm types in the EU (e.g., Kokemohr et al. 2022) in the context of policy impact assessment (e.g., Kuhn et al. 2019) and technology evaluation (e.g., Kuhn et al. 2022). In its current form, it is realised as a modular template design model that can simulate multiple farm branches at a single farm scale. A schematic overview of the model and the analysed system boundaries are depicted in Figure 4.1 below; complete model documentation can be found online[3].

In FarmDyn, each farm is modelled as an individual entity, and its management (including cash crop, fodder crop, and dairy production) is optimised subject to boundary conditions such as prices or farm endowments. Farm management options include, among other things, which animals to keep, how to feed them, which crops to grow and how to fertilise them, and how to manage pastures and meadows (means of harvest, fertilisation, pasture periods, etc.). Herd demographics (calving, raising periods, replacement, and selling) are captured monthly. Feed requirements are calculated by considering dry matter, fibre, protein, energy, animal performance, and lactation periods according to the feed planning tool Zifo2 (LFL, 2016). The requirements can be met with various bought concentrates and self-produced roughages and grazing. The nutrient contents in each feed are taken from LFL (2020). Grassland is differentiated through harvest (silage, hay, baling, grazing), seasonality, productivity, and harvest quality. Crop production options are farm-specific, considering the respective yields, fertiliser needs, and land endowments. The model is calibrated to the FADN farms by restricting the solution to the given endowments of land, labour, and the available production technology (stable system, mechanisation, yield, etc.).

[3] https://farmdyn.github.io/documentation/

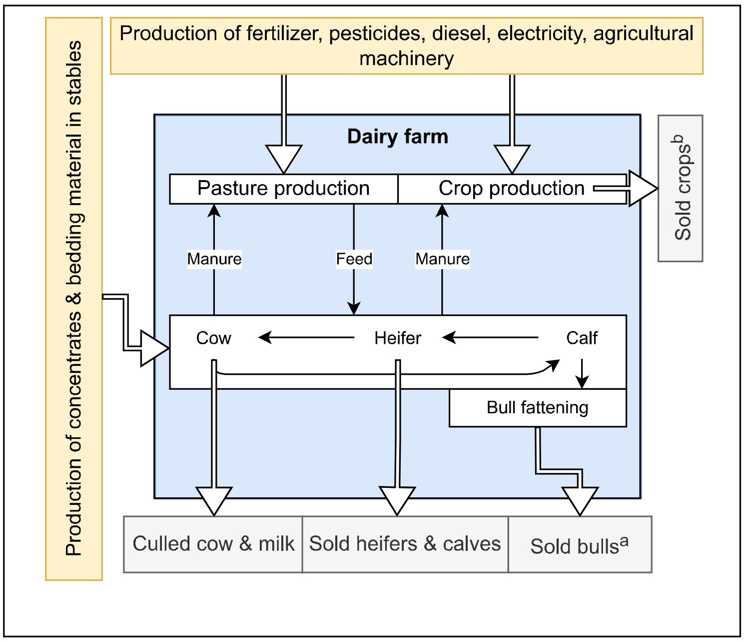

Figure 4.1 Overview of FarmDyn template model and system boundaries. “a” Bulls are only produced in VL, TR.flat, and TR.hill. “b” Arable crops are only made in TR.flat.

4.2.3 *Parameterization*

Past applications of FarmDyn had a regional focus on Western European countries in the European Union, which differ substantially in pedo-climatic conditions, farm structure, and active policies from Norway. Accordingly, the model is parameterised to local conditions by I) adapting prices and changing the currency to NOK, II) adapting yield levels of crops, grasslands, and pastures and the according fertiliser requirements, III) introducing breed characteristics of the Norwegian Red cow breed by adjusting reproductive traits, process length, and weights and yield levels (meat yield, milk yield), and IV) adapting production technology (mechanisation level, stable endowments). The data was collected from Norwegian farm planning data (Ebbesvik, 2020), personal communication with the Norwegian farm advisory service, and gathered on existing Norwegian farms in collaboration with the farming community during the Climplement project.[4] Where Norwegian data is unattainable, the model's default settings, based on Achilles (2016), are utilised.

The Norwegian agricultural policy environment is added to the model. This includes a detailed description of the seasonal fertiliser restriction, subsidies on production technology (manure application), degressive payment schemes for animal husbandry (dairy, beef, suckler cows), grazing schemes, price premiums for beef and milk, small farms schemes, and regionalised payment levels differentiated by municipality. All policies are combined in a new policy module.

4.2.4 *MACC derivation*

The optimisation process of the model is used to estimate MACC. Abatement costs are calculated in an iterative process, starting with a baseline run where the farm profit and emission level are calculated. Relative to the baseline run, an emission cap is implemented, and the model maximises the profit subject to the restricting emission cap. The difference in profit of this run compared to the preceding baseline run is the abatement cost calculated as profits foregone through abatement. This process is repeated with stepwise reduced emission caps to create an abatement cost curve. The change of the total abatement costs between steps divided by the change in abated GHG emissions leads to net on-farm marginal abatement costs (Lengers et al., 2013).

4.2.5 *Emission calculation*

Lengers et al. (2013) show that MACC depends on the assessed indicator for GHG emissions. Since this analysis is motivated by the national effort of GHG abatement, we employ the GHG emission calculation methodology in Norway's National Inventory Reporting (NIR) under the Kyoto Protocol (NIR 2020). Figure 4.2 depicts the scope of the emissions calculation and the included emission sources and sectors.

[4] https://climplement.no/?lang=en

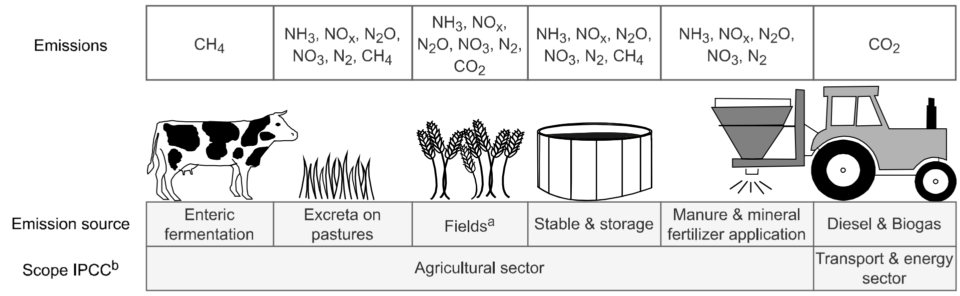

Figure 4.2 The scope of the emissions calculation in the analysis, according to NIR (2020). "a" Field emissions include emissions from liming and crop residues. "b" Sectors differentiate GHG emissions. Source: Own illustration

Figure 4.2 summarises the considered pollutants, sources and sub-sources, the underlying methodology, and the accuracy divided into three tiers defined by Buendia et al. (2019). Considered emissions and sources are methane (CH_4) from enteric fermentation, ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), and nitrate (NO_3-) from manure handling in stables and storages, NH_3, NO_x, N_2O, and NO_3- from fertiliser application, manure application, crop residues and excreta from grazing animals, CH_4 from excreta of grazing animals and carbon dioxide (CO_2) from liming. Although not directly contributing to global warming, NH_3, NOx, and NO_3- emissions are used to calculate indirect N_2O.

Source / Sub-source	Pollutant	Methodology	Tier
Enteric fermentation	CH_4	Calvo Buendia et al. (2019)	3
Manure management	CH_4	Calvo Buendia et al. (2019)	2
	NH_3, N_2O, NO_x, N_2	EEA (2016)	2
Pasture	CH_4	Calvo Buendia et al. (2019)	2
	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	Calvo Buendia et al. (2019)	1
Field & Pasture / Manure application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	Calvo Buendia et al. (2019)	1
Field & Pasture / Fertilizer application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	Calvo Buendia et al. (2019)	1
Field / Lime application	CO_2	Calvo Buendia et al. (2019)	1
Field / Crop residues	N_2O, N_2	Calvo Buendia et al. (2019)	1
Field & Pasture	NO_3^-	Calvo Buendia et al. (2019)	1
Indirect N_2O	N_2O	Calvo Buendia et al. (2019)	1
Diesel	CO_2	Calvo Buendia et al. (2019)	1

Table 4.2 Considered emissions, sources, and methodology

Nitrogen (N) flows used for calculating NH_3, NOx, and N_2O emissions are modelled based on the stepwise approach proposed by the EEA (2016), meaning that N is considered in two pools: ammonium N and total N. The respective N pools are deducted by N losses at every handling step, resulting in a consistent N flow. Losses of gaesous N (N_2) are considered for the N-mass flow, albeit not contributing to global warming.

CH_4 from enteric fermentation contributed 51% of the agricultural sector's emissions in 2018 (NIR, 2020). Due to its immense contribution to overall emissions, a detailed approach for calculating CH_4 emissions from dairy cows is used, which considers the gross energy intake, milk yield, and the share of concentrates in the diet (Schwarm et al., 2019). The approach is also used in NIR (2020).

Emissions from producing primary farm inputs are not considered, as these are reported in other sectors (NIR, 2020). Likewise, emissions from burning diesel in agricultural machinery are commonly reported in the transport sector. However, such emissions are also part of the Farmers Union's action plan to mitigate emissions (Norwegian Farmers Union, 2020) and are therefore included in the analysis. The GHG emissions are summarised into CO_2eq, multiplying each pollutant with the respective characterisation factors 25 for CH_4, 298 for N_2O, and 1 for CO_2 (IPCC, 2007).

4.2.6 *Abatement technology*

In the study, the abatement measures are chosen based on the applicability of the national effort stated in the intentional agreement. This only includes measures theoretically captured in the GHG emissions calculation methodology from the NIR (2020). This captures explicit technology options (manure storage cover, manure application technology, biogas fermentation, biodiesel), herd management decisions (replacement and herd size management, feed composition), and grass and cropping decisions (fertilisation decision, grazing management, crop growing decisions, intensity management, land abandonment). Measures that are legally not allowed are excluded, such as feed additives (NIR, 2020).

4.3 **Results**

4.3.1 *Baseline results*

The GHG emissions of the seven farms in the baseline are presented by emission sources in Figure 4.3. The total emissions per farm range between 96 (ØL) and 300 t CO_2eq per farm (VL). The largest share of emissions is enteric fermentation, averaging roughly 70% of total emissions on all farms, followed by emissions from stable and storage (10-12%) and manure application (9-10%). Accordingly, the farms with more animals tend to have the most significant emissions. Emissions from burning diesel, mineral fertiliser application, and fields and pastures have a minor share.

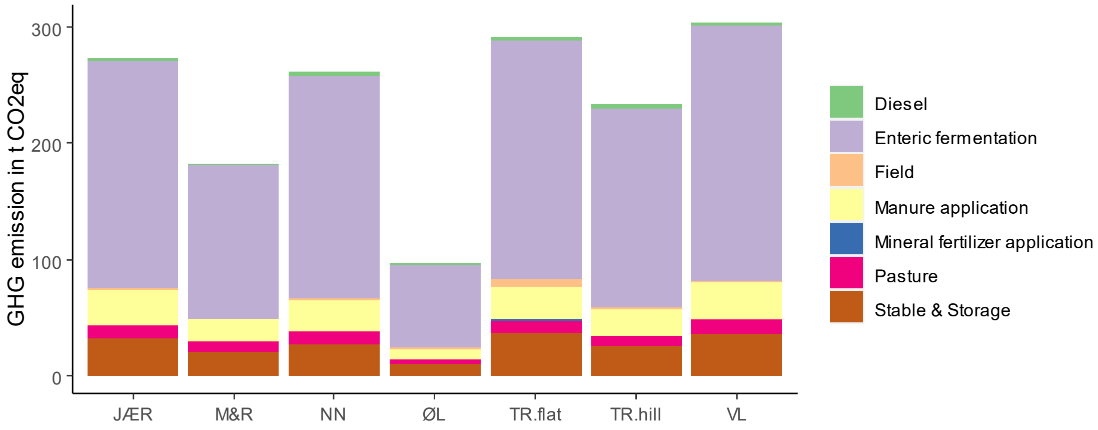

Figure 4.3 Greenhouse gas emissions of the dairy farms in the baseline

The variable costs of the seven farms are depicted in Figure 4.4. TR.flat operates at the highest variable costs with 700 k NOK, followed by VL (507 k NOK), JÆR (500 k NOK), NN (396 k NOK), M&R (333 k NOK), TR.hill (297 k NOK), and ØL (111 k NOK). The highest share of costs is bought concentrates for feeding, ranging from 30.7% in ØL to 65% in TR.flat. Large farms and farms with a high stocking density tend to have higher costs (VL, TR.flat & JÆR).

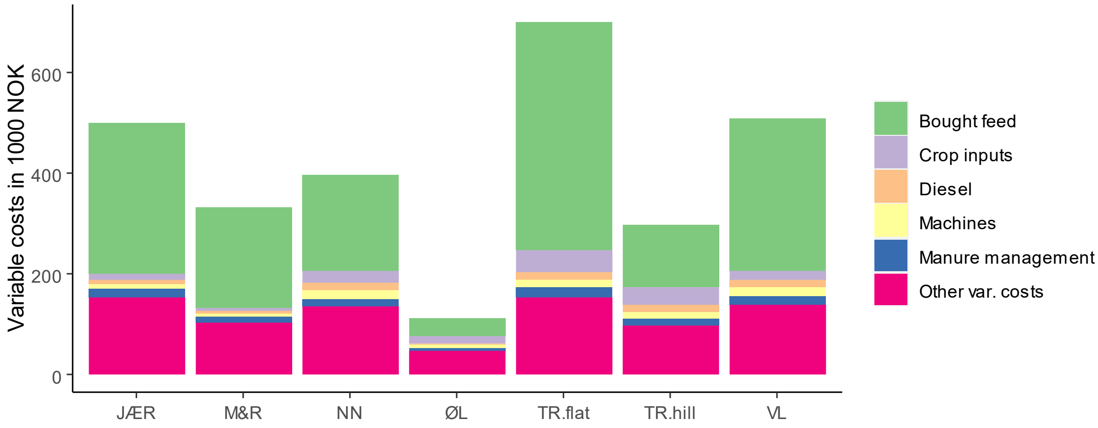

Figure 4.4 Variable costs of the farms in the baseline

The farms' incomes from revenues and premiums are shown in Figure 4.5. The highest revenue is observed in VL with 3663 k NOK, followed by TR.flat (3655 k NOK), NN (3246 k NOK), JÆR (2773 k NOK), TR.hill (2637 k NOK), M&R (2233 k NOK) and ØL (1190 k NOK). On all farms, the largest share of revenues is from selling milk, ranging between 38% in TR.hill and 62% in JÆR. The total share of all premium payments averages between 26% (JÆR) and 49% (ØL). In VL, TR.flat, and TR.hill, roughly 10% of revenues arise from bull beef production.

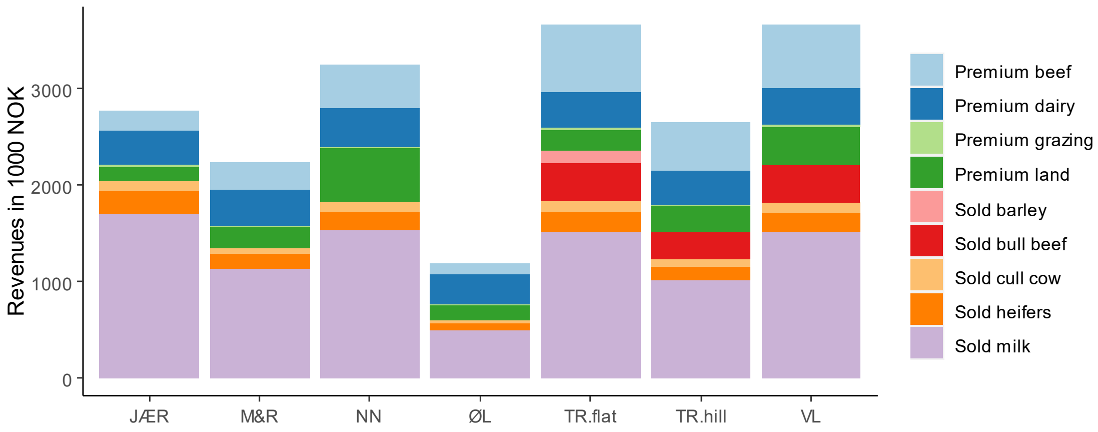

Figure 4.5 Revenues and received premiums of the farms in the baseline.

4.3.2 *Marginal abatement cost curves*

Figure 4.6 depicts the resulting marginal abatement cost curves for the seven farms. It shows the marginal abatement costs expressed in NOK per t CO_2eq abated GHG emissions compared to the baseline. The curves follow a familiar pattern: a sharp rise in costs at low mitigation efforts and a slower growth at higher abatement efforts. The tipping point from the initial sharp rise to moderate price increases is between 2% (NN, ØL, TR.hill) and 4% mitigation (JÆR, M&R, TR.flat).

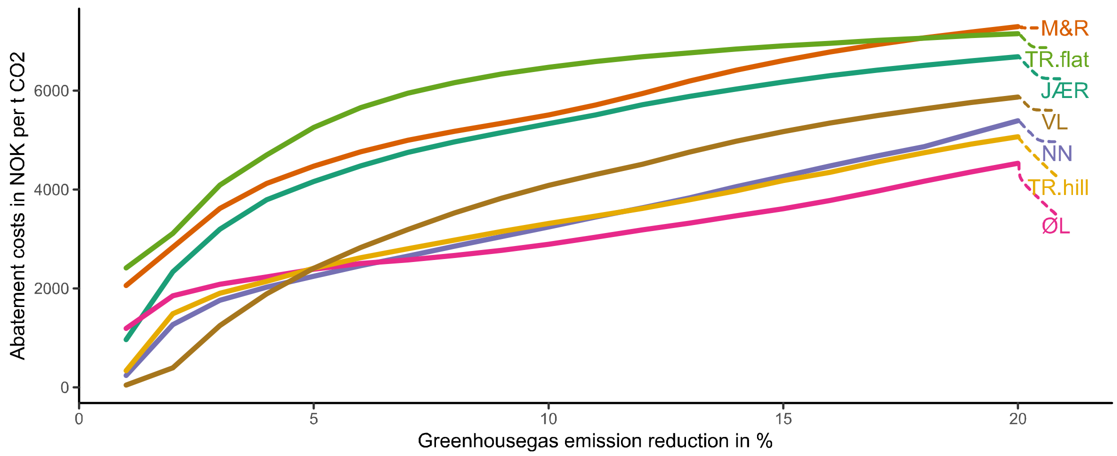

Figure 4.6 Marginal abatement cost curve of representative Norwegian dairy farms

None of the analysed farms can achieve substantial emission savings at the current carbon price of 2000 NOK per t CO_2eq. Especially the farms Jær, M&R, and TR.flat have high marginal abatement costs. For example, in M&R, abatement costs at 1% emission reduction sum up to 2057 NOK per t CO_2eq and reach 7294 NOK per t CO_2eq at 20% abatement. On the farms ØL, NN, and TR.hill abatement at costs under 2000 NOK per t CO_2eq, it seems possible to achieve lower abatement steps by up to 4%. In TR.hill, costs sum up to 336 NOK per t CO_2eq at 1% abatement and 5067 NOK per t CO_2eq at 20% abatement. The farm VL stands out in that it starts with the lowest costs at 1% (42 NOK per t CO_2eq), followed by a slight rise until 2% (392 NOK per t CO_2eq), a higher increase surpassing the costs of NN, ØL, and TR.hill at around 5% and reaching 5871 NOK per t CO_2eq at 20% abatement.

4.3.3 *Abatement strategies*

On all farms, low-cost abatement efforts are realised through a change in the animal feed and, for some farms, a reduction in the age of the first calving of heifers. The latter spares CH_4 emissions from enteric fermentation by reducing the number of unproductive animals in the herd. The farm JÆR, for instance, reduces the age of first calving by 30 days. The associated emission reduction is small and well below 1% of the total emissions. A higher energy density in the feed composition of dairy cows lowers CH_4 emissions from enteric fermentation. Plot P1 in the appendix shows the average daily ration of the dairy cows in kg dry matter (DM). For example, in ØL, on average, 2.64 kg DM concentrates per cow and day are fed in the baseline, increasing to 4.06 kg DM at 5% abatement. The tier-two approach in emissions calculation captures the effect only for dairy cows. The methodology for calves, heifers, and bulls is missing (NIR, 2020). Further changes in the ratio, such as increasing the share of metabolisable energy compared to gross energy, can mitigate emissions from enteric fermentation of heifers, bulls, and calves. All farms take up this strategy. Figure 4.7 shows emissions from enteric fermentation per livestock unit (LU) on the farms at different abatement levels. A substantial decline in emissions can be observed on all farms. Farms with lower marginal abatement costs (ØL, NN, VL, and TR.hill) have higher emissions of enteric fermentation, summing up to 3669, 3772, 3642, and 3780 kg CO_2eq, per LU in the baseline, respectively. JÆR, M&R, and TR.flat start with lower emissions at 3399, 3362, and 3210 kg CO_2eq per LU, indicating their higher efficiency in feeding at the baseline. At 20% abatement, emissions from enteric fermentation per LU are reduced by 8-14% in Jær, M&R, and TR.flat and 14-23% in ØL, NN, VL, and TR.hill.

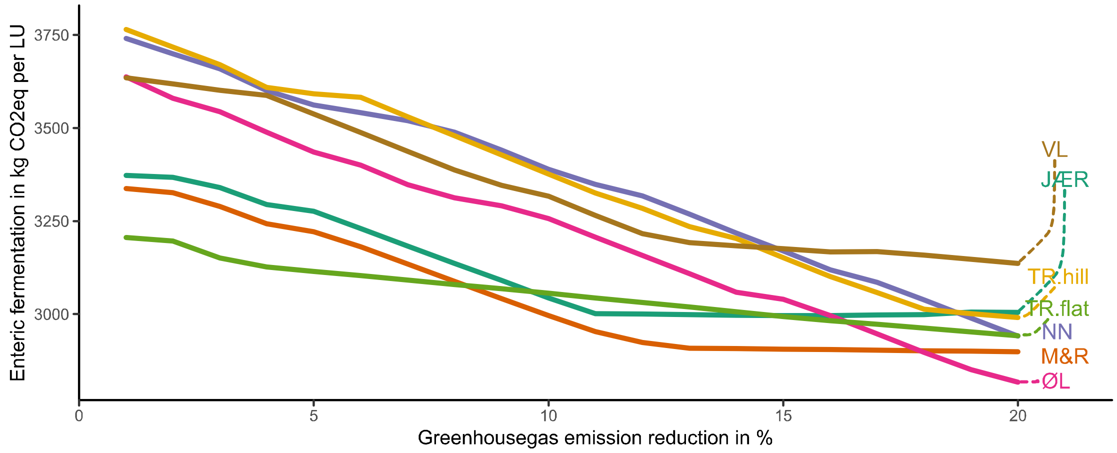

Figure 4.7 Emissions from enteric fermentation per livestock unit on representative Norwegian dairy farms at different abatement levels.

However, the ability to abate emissions by changing the feed composition is limited. Bovine animals require a minimum amount of fibre from roughages for their rumen to work. Due to the already high portion of concentrates in feeding in JÆR, M&R, and TR.flat in the baseline (between 6.66 kg DM M&R and 9.28 kg DM per cow and day in TR.flat), these farms have little leeway to optimise further the feed regarding CH_4 emissions and thus face higher abatement costs. The flattening curves in Figure 4.7 emphasise this. For TR.flat, the maximum increase of the concentrate share is reached at 5% abatement at 10.19 kg DM per cow and day, corresponding to roughly one-third of the DM weight of the total ration. The initial share of concentrates in a cow's ration in the baseline, and therefore the potential to further increase it to abate emissions, is primarily determined by the availability of roughage on the farm and the cow's yield potential.

In case of limited possibilities to abate emissions through feed optimisation, farms must rely on other abatement strategies to meet the emission mitigation targets enforced in the analysis. As described above, investments in explicit abatement technologies like biodiesel and low-emission manure application devices can be observed on all farms once the limits of optimising feeding practices are reached. The switch from diesel to biodiesel saves emissions because biodiesel is produced from regenerative sources and, therefore, is not considered in the emission calculation following the methodology of the NIR (2020). The farms JÆR, M&R, and TR.flat implement biodiesel at a reduction level of 2%. The farms VL, TR.hill, NN, and ØL switch at 4%, 5%, 6%, and 9%, respectively. However, biodiesel has limited abatement potential because emissions from burning diesel only have a share of around 1% of total emissions in the baseline. The change from conventional diesel to biodiesel is assumed to mitigate these emissions completely.

Low-emission manure application devices refer to the switch of manure application with the typical broad spreader to the advanced trailing shoe and injection application technology. This lowers NH_3 emissions and, therefore, reduces indirect N_2O emissions. On grassland, the advanced technology can reduce NH_3 emissions by up to 40%, of which 1% turns into N_2O. Manure application accounts for around 10% of emissions in the baseline. Graph P2 in the appendix depicts the average annual amount of manure applied in m^3 for each farm at different abatement levels. Adopting the new technology has already resulted in a 1% abatement on most farms. However, only a fraction of the manure is applied with advanced technology at lower abatement efforts. The farms JÆR, M&R, and TR.flat completely replace the broadspread application technology with trailing shoe application at an abatement level of 4-5%. A further change to injection application happens in JÆR and M&R at 11-12%. The other farms adopt the technology at later stages. Across all farms, adopting advanced manure application technology mitigates around 2% of baseline emissions. Other optional technologies are either already implemented on farms, such as manure storage coverage (NIR, 2020), or are too costly to implement on the analysed farms and at the assessed reduction steps (biogas).

Once these measures are utilized to their full potential, herd size reductions are the only measure to further abate emissions. This first affects farms with high stocking density (JÆR, M&R, TR.flat). Figure 4.8 depicts the stocking density in LU per farmed area on the seven farms at each abatement step. The farms JÆR, M&R, and TR.flat have the highest livestock density with 1.3, 1.1, and 1.4 LU per ha, respectively, implying the lowest roughage production per animal.

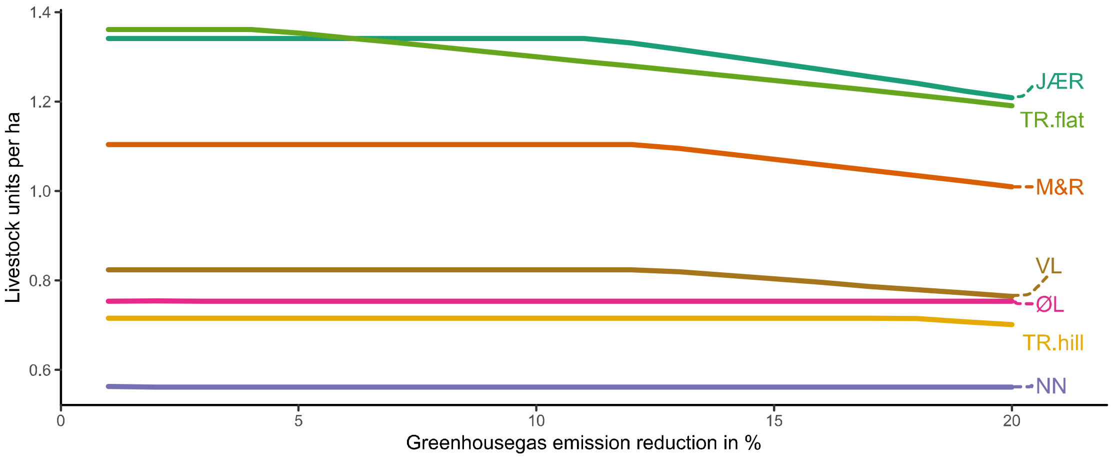

Figure 4.8 Livestock units per ha on representative Norwegian dairy farms at different abatement levels

The farms VL, TR.flat, and TR.hill fatten bulls as a side business besides dairy production. However, fattening only contributes around 10% to overall revenues and is, therefore, less profitable than dairy production. Accordingly, these farms reduce their bull herd before adjusting their dairy herd to mitigate emissions. At 20% abatement, the reduction of the bull herd reduces income from sold bulls by 47% in VL, 82% in TR.flat, and 13% in TR.hill.

The farms JÆR and M&R reduce their dairy herd, reducing the income from sold milk by 10% and 9% at 20% emission reduction, respectively. The farms ØL and NN can reach the set targets solely by optimising the feeding and investing in biodiesel and manure application technology. Therefore, they are the only farms that maintain the production level from the baseline.

4.4 Discussion

The study is the first approach to calculate abatement costs for Norwegian dairy farms. Table T1 in the appendix summarises studies that calculate abatement costs of dairy farms, their methodology, main findings, and promising abatement strategies. Studies with a different regional scope confirm our findings that substantial savings on farms are bound to high costs (Mosnier et al., 2019; Cecchini et al., 2018). However, Lengers et al. (2014) and Mosnier et al. (2019) find lower abatement costs for the first 5% of abatement. The abatement costs in the literature range from 20 € per t CO_2eq to 243 € per t CO_2eq (~200 – 2430 NOK) and are, therefore, substantially lower compared to the costs calculated in this study (Mosnier et al., 2019; Wettemann et al., 2017; Cecchini et al., 2018; Lengers et al., 2014). The difference can be traced back to the investigated abatement options, the generally lower farm size, the support policies specific to the Norwegian setting, and the overall scope of the analysis. Due to the comparably high coupled production support, the representative Norwegian farms have higher opportunity costs to deviate from their current farm management.

Prevalent abatement measures differ between studies depending on the scope and methodology used. Among others, they include improvements in fertilisation to spare nitrogen usage, measures to increase the efficiency of cows (lifetime prolongation, health improvement), feed optimisation, and moderately increasing the land use intensity (Wettemann et al., 2017; Duffy et al., 2021 Mosnier et al., 2019). Feed optimisation and improvements in fertilisation (manure application) have also been identified as dominant abatement strategies in this study. The other abatement strategies are partially out of scope because they are not captured in the model (lifetime prolongation of cows), are less efficient than other measures (land use intensification), or are not accounted for in the GHG emission accounting (animal health).

The emission accounting follows the NIR under the Kyoto Protocol as this is the methodology used to measure the national effort of emission abatement (NIR, 2020). The current revision of the NIR (2020) also includes a new approach to measure CH_4 from enteric fermentation of dairy cows, considering the effect of higher amounts of concentrate feeds. The study is the first to utilise this methodology in calculating abatement costs. Potential reductions of CH_4 from enteric fermentation resulting from other feed optimisation measures, like improvements in roughage quality or feed additives, are not included (NIR, 2020). Their consideration potentially lowers the abatement costs, but it remains questionable how improvements in roughage quality can be induced by policy and monitored at the farm and national scale.

Using the single farm optimisation model FarmDyn offers the advantage of a detailed technology description, including interaction effects between mitigation measures and their impact on farm activities. However, information about individual mitigation measures can be complex and challenging to single out, given the interaction of measures (Eory et al., 2018). Using single-farm models allows us to assess diverse farms and gain insights into MACC differences within the farming population. The farm sample is selected following a cluster analysis based on FADN data to obtain typical farms that represent the variation of Norwegian dairy farms. Results differ among farms, which underlines the necessity to account for farm heterogeneity and gives valuable insights for policy recommendations. However, concluding at the sector level still proves difficult based on single-farm results (Lengers et al., 2014). A larger farm sample or sector model approach could gain further insights about the sector to complement the used approach (Eory et al., 2018). The latter would also allow for consideration of market effects and analysis of potential emission leakage.

The FarmDyn model follows standard economic assumptions on farmer behaviour, leading to a cost-efficient selection of inputs and management strategies for the realised farm activities. These assumptions exclude GHG abatement due to improved efficiency at no costs or even cost savings that would result in negative abatement costs. These could, for example, be realised by improved N fertiliser or feeding management. However, estimating this potential at the farm level is challenging as relevant information is not part of official statistics and is often unknown to farmers.

Different instruments of agri-environmental policies are available for GHG mitigation, such as economic (e.g., tax on emission), command-and-control (e.g., ban of certain technologies), information, and support instruments. Instruments related to farms' GHG emissions directly enable farmers to select the most cost-effective measures. However, as GHG on farms have non-point sources and are difficult to measure, such instruments require an indicator for the emission savings related to the relevant abatement measures (Lengers et al., 2013). For example, a tax on livestock numbers would disregard the low-cost abatement measures and lead to high abatement costs. Our results show that all farms adopt feeding and herd management as the first measures. Such adaptions' GHG emission reduction effect is complex, costly to estimate on farms, and challenging to control. Therefore, informational instruments in combination with financial compensation might be the most promising approach and a likely implementation as the farmers' union oversees the farm-level abatement in the intentional agreement.

The Norwegian agricultural policy strongly emphasises strengthening farm income and preserving production levels. GHG abatement policies need to be designed in coherence with these goals. Our results show high marginal abatement costs at higher abatement levels, which translates into a loss of profit between 10% in (NN) and 20% (JÆR) at 20% abatement relative to the baseline. Almost all analysed farms reduce their herd size to reach comparably high abatement targets, lowering their milk and beef production. This causes a substantial income loss for farmers and a possible reduction in food production, as well as conflicts with other policy goals, such as strengthening the income of farms or securing food production. To address these problems, appropriate compensation for realised measures might be needed to align with the otherwise contradicting policy goals of farm income and GHG emission mitigation. However, our results show the heterogeneity of abatement costs, which also require variable compensation to avoid windfall gains.

The switch to biodiesel and the increase of concentrates in the animals' ration are found to be lower-cost abatement measures. The production and provision are outside the farm boundaries and, therefore, not considered in the emission accounting. Therefore, this poses the danger of emission leakage and might counteract meaningful abatement (Arvanitopoulos et al., 2021; Khanna et al., 2011). Moreover, higher shares of concentrates and higher energy balances in the animals' ration can adversely affect animal health, e.g., clinical ketosis or fatty liver syndrome (Collard et al., 2000).

Advanced manure application technology is a viable option for GHG mitigation by reducing indirect emissions. This might also reduce the amount of mineral N fertiliser needed, which could increase its efficiency (Aguirre-Villegas & Larson, 2017). However, this is not observed in the study at hand because farms already had an excessive amount of manure for fertilisation. Advanced manure application technology is already part of a subsidisation scheme. Still, only a limited abatement potential of up to 2% is achieved by enhanced manure application in this study.

Generally, the high abatement costs, the possible conflicts with other policy goals, the risk of emission leakage, and the abundance of promising abatement technology raise the question of whether the goal of the intentional agreement is attainable. The government proposed a carbon tax of 2000 NOK per ton CO_2eq in its white paper on climate policy (Norwegian government 2021). Our results suggest that only a few farms can abate emissions at such costs and only to a limited extent (up to 5% relative to the baseline) at such costs. The realised emission savings fall substantially below the ambitious targets set in the intentional agreement. If abatement costs of the selected dairy farms are higher than the average in the agricultural sector, the intentional agreement could be achieved cost-effectively by abating on other farms. However, as most emissions in Norwegian agriculture are related to cattle farming and we selected representative farms, we hypothesise that achieving the emission target in the intentional agreement implies marginal abatement costs above the carbon tax of 2000 NOK per CO_2eq proposed by the Norwegian government.

Due to the high costs of the sector's abatement effort, the other elements of the mutual agreement (food waste reduction and dietary change) may be more feasible. The Climate Cure 2030 report contains mitigation measures, including dietary change and food waste reduction, that far exceed the climate ambition in the intentional agreement (Norwegian Environment Agency, 2020). Dietary changes that bring the current diet more in line with official dietary guidelines are estimated to cut 2.9 million t CO_2eq in the 2021-2030 period. These changes imply, among others, a reduction in red and processed meat consumption and an increase in fruits and vegetables. Reducing food waste in the food value chain from producer to consumer adds another 1.5 million t CO_2eq in emission cuts. Therefore, these two measures alone would be almost sufficient to achieve the target set by the intentional agreement. Despite the possible advantages for human health and the environment, policymakers should be aware that a dietary change with less red meat consumption could reduce income for cattle farmers through market effects and again interfere with other policy goals.

4.5 Conclusion

The optimisation model FarmDyn calculates MACC for 7 Norwegian dairy farms selected from FADN data by cluster analysis. This study has extended the model to represent active Norwegian farm policies and up-to-date GHG emission accounting methodology reported in NIR (2020). The analysis shows that under a carbon tax of 2000 NOK per t CO_2eq, realised emission savings are small, with at most 5% of farm-level abatement achieved by only four farms with comparably low livestock densities. Low-cost abatement strategies include replacing regular diesel with biodiesel, using advanced manure application technology, and increasing the shares of concentrates fed to dairy cows. The resulting high abatement costs reveal conflicts between the government's ambitious GHG reduction plans and other policy goals like securing farm income and maintaining food production levels. Future research should extend the analysis to a larger farm sample to calculate the MACC of the whole sector and further elaborate on the impact of farm heterogeneity. The application of global models could analyse possible emission leakage of abatement measures. In light of high abatement costs, as shown for the dairy sector in the preceding analysis, the targeted contribution of farm-level abatement measures to Norway's national mitigation efforts should be defined carefully and under consideration of potential compensation payments to address impending policy trade-offs.

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Chapter 5
Conclusion

The European cattle sector is criticised for its negative external effects on the environment, especially its contribution to climate change. Given its economic and cultural importance, it is likely not to vanish in the coming years and is expected to adapt its means of production. This thesis aims to 1) assess the economic, social, and environmental impact of prevalent European production systems, 2) analyse potential innovations to improve and alleviate the environmental pressure, and 3) calculate the costs of a potential emission reduction. This chapter summarises the contribution of the thesis described in previous chapters. The methodology is critically discussed, and a research outlook is given. The thesis concludes with a policy discussion considering the ongoing debate on cleaner means of production in the sector.

5.1 Major contributions of the thesis

The thesis offers new insights into the sustainability of European cattle production systems, particularly those found on typical farms. It supports the importance of sourcing calves for European bull beef production systems, revealing that dairy-breed calves lead to more favourable environmental indicator scores than specialised beef breeds. This is due to the partial allocation of impacts toward dairy production, potentially reducing GWP by up to 60%. Additionally, the allocation towards dairy production reduces the work time needed for herd replenishment.

Furthermore, the thesis shows higher profitability of beef-breed systems compared to those employing dairy breeds for beef fattening, despite lower production costs in the latter. This emphasises the importance of beef prices in determining profitability. Introducing fast rotational grazing practices and cattle crossbreeding emerge as strategies with the potential to augment farm profits, albeit at the cost of increased labour inputs.

All analysed beef production systems are identified as net consumers of feedstuff potentially consumable by humans, thereby showcasing the contribution of beef production to feed-food competition. The thesis points out promising innovations to enhance food production efficiency, namely increased usage of industry by-products and grasslands for feeding and matching the stocking density to the available roughage area. With these adjustments, some beef farms could be transformed into net producers of human consumable protein.

The impact of parametric uncertainty on sustainability analysis outcomes is assessed, including fluctuations in essential farm input- and output prices and spatial and biological variability within the system. Parameters such as beef prices, calf costs, the yield of roughage crops, and animal traits are identified as influential for the environmental, social and economic performance. They could be used as potential levers for enhancing the sustainability of the analysed systems.

Moreover, the thesis adds marginal abatement cost curves for typical Norwegian dairy farms, revealing feasible emission reductions of up to 5% below the proposed Norwegian carbon price threshold of 2000 NOK per t CO_2eq. The most promising mitigation option is optimising animal feed rations towards higher energy density, which can lead to potential savings of 8% to 20% of emissions from enteric fermentation. Other cost-efficient measures identified are transitioning from fossil fuels to biofuels and adopting advanced manure application technology. However, higher abatement efforts incur substantial costs as they are realised through herd size reductions. Efficient farms with high stocking density face higher costs, as they lack the potential to optimise animal diets further.

Finally, the presented research is linked to far-reaching model developments. The FarmDyn model is parameterised to suit Norwegian conditions, encompassing prices, policies, and emission accounting. In addition, it introduces a novel consideration of concentrate feed shares in calculating emissions from enteric fermentation, which influenced the Marginal Abatement Cost Curves considerably. Additionally, it integrates a Lifecycle Sustainability Analysis framework with a comprehensive set of indicators covering environmental, social, and economic dimensions, further enhancing the model's utility and applicability in sustainability assessments. This includes integrating the Ecoinvent database, environmental impact assessment methodology, accurately tracking and distributing impacts along the life cycle of agricultural outputs and adding the economic allocation of impacts between co-products where applicable.

5.2 Methodological discussion and research outlook

The bio-economic farm model (BEFM) FarmDyn is used throughout the thesis to evaluate the sustainability of European cattle farms. BEFMs have several advantages that make them especially suited for this task. They enable a highly detailed description of production processes and technology, capture the peculiarities of individual farms, and thereby help to understand the implications of the heterogeneous European cattle production systems (e.g. Blanco, 2016; Mack & Huber, 2017). They include detailed material and financial flows, which provide inventory data to calculate environmental, economic, and social indicators. They mimic the farmer's decision-making by showcasing an individual’s profit-maximising strategies, allowing BEFMs to depict responses to detailed agricultural policies targeted at the farm level (Janssen & Van Ittersum, 2007).

However, due to their nature as supply-side models, they lack the integration of market feedback. This can have implications for the presented research as price changes for inputs and outputs in response to the assessed measures may influence the produced quantities and, ultimately, the presented results through adjustments in farm management. For example, the sensitivity analysis in Chapter 2 showcases that the results are sensitive to changes in the beef price and, thereby, beef supply. Sector or market models, for example, partial equilibrium models such as the CAPRI model (e.g. Blanco et al., 2017) or general equilibrium models such as CGEBOX (e.g. Wilts et al., 2021), can include such market feedback but usually lack the detail and farm-level focus provided by BEFMs.

Furthermore, focusing on individual farms' profit maximisation neglects other behavioural particularities that might impact farm management. For example, Chapters 3 and 4 assess the potential of management innovation and technology to improve the farm's sustainability of production, whereas the level of implementation is based on economic rational behaviour assuming perfect information on the technology or innovation. However, other factors such as uncertainty, risk perception, cognitive and emotional processes, social interactions, and personal circumstances can affect farmers' final decisions and course of action (Bartkowski & Bartke, 2018; Dessart et al., 2019). One way to address these factors in ex-ante impact assessments is to implement other behaviours beyond standard economic assumptions in the objective function of the BEFM, such as including risk factors or multi-criteria approaches (Janssen & Van Ittersum, 2007). In addition, agent-based models (ABM) capture behaviour and interaction among agents and thereby help to understand farmers' responses to changing conditions (Huber et al., 2018). In the case of management innovation and novel technologies, ABMs could contribute to adoption and diffusion behaviour, which is valuable in disseminating promising technologies.

Nevertheless, spatially higher aggregated market models and ABMS miss the detailed description of production technology needed to capture farm heterogeneity and assess technological and management innovations at the farm level (Blanco, 2016). The three approaches should, therefore, complement- but not substitute each other. This can be done for instance by coupling BEFMs with ABMs or market models to overcome the limitation of the farm-level focus regarding interactions and market feedback.

The LCSA approach in Chapter 2 examines potential trade-offs and co-benefits between different sustainability dimensions of beef production. For this purpose, the bio-economic model FarmDyn provides life cycle inventory data to calculate impacts. The combination of the two approaches enables predictions of impacts induced through changes in boundary conditions and, ultimately, decision variables, such as land-use change resulting from policy measures (Nakashima & Ishikawa, 2017). Furthermore, in their nature, these models offer an integrated framework that readily provides information on socio-economic and environmental indicators (e.g. Glithero et al., 2012; Weiss & Leip, 2012). Besides this, optimisation models like FarmDyn offer other potential use cases for LCA practitioners. For example, they can be used to allocate impacts in multioutput systems, identify potential improvements in the system by optimising the system on different objectives, or, if all impacts are combined in a single score, even determine the overall optimum of the system (Azapagic & Chift, 1998). However, problems can arise as linear programming models such as the applied BEFM suffer from bumpy behaviour due to corner-point solutions (Howitt, 1995a; Howitt, 1995b), and the validation of models in their representation of real-world conditions can be difficult (Britz et al., 2021). This causes their application to be more challenging than standard approaches to conduct LCA or LCSA.

The chosen quantitative approach enables the computation of several environmental and economic indicators but needs more details on social aspects. Sanou et al. (2023) find that there is no standard nor a set of indicators to assess the social sustainability of agri-food systems. Additional information and data are needed to assess the impact of cattle production on stakeholders along the supply chain. This includes empirical validation of measuring social sustainability (Sanou et al., 2023). Also, quantitative approaches could be amended with qualitative methods regarding the social welfare of production.

Animal welfare is a declared policy goal across Europe (European Commission, 2020), which was not addressed in the thesis. Despite its relevance, a standardised methodology and indicators following the life-cycle approach are scarce (Lanzoni et al., 2023). Animal welfare can be subjective and differ between individuals in a batch of animals and during an animal's lifetime. Gathering and combining information on animal welfare along the supply chain into one indicator proves difficult. Due to these aspects, comparing different production systems in terms of their impact on animal welfare becomes intricate (Scherer et al., 2018). Therefore, consolidated action is needed to create a workable indicator that links production processes to animal welfare.

Similarly, despite being a declared policy goal, the thesis does not cover biodiversity conservation (European Commission, 2020). There are LCA capturing biodiversity, but they have far-reaching shortcomings, such as the exclusion of agricultural intensity, that are crucial to evaluate cattle production (Gabel et al., 2016). Again, a standardised methodology that includes data sets to quantify and compare indicators that cover all dimensions comprehensively is lacking (Damiani et al., 2023). The relationship between cattle production and biodiversity is complex, as certain species may thrive due to cattle farming while others risk endangerment (Kok et al., 2020). Furthermore, biotopes vary in their spatial scale and may reach beyond the confines of individual fields or farms, often affecting whole landscapes. These landscapes differ across Europe, complicating the comparison of systems in their contribution to conservation efforts (Kok et al., 2020). Innovative and nuanced approaches are needed to assess the interaction between beef production and biodiversity to understand the issues at different scales.

The thesis emphasises the importance of considering farm heterogeneity and detailed production technology. The farm data needed to parameterise FarmDyn with such detail is gathered from different sources. The respective approaches in this thesis reflect a careful balancing of data depths, consistency, and accuracy needed to capture the individual farm's characteristics as well as the representativeness and scalability of the results. The expert-driven typical farm approach in Chapters 2 and 3 offers an extensive description of production technology and data depths needed to calculate the LCA indicators. It enables the comparison of production systems and farm types regarding their competitiveness and sustainability (Isermeyer, 2012). While Chibanda et al. (2020) argue that typical farms can be representative of a region or farm type, drawing causal relationships and inferences about larger populations based on the small sample size is limited. In Chapter 4, a subsample of representative FADN farms is chosen via cluster analysis. This enables scaling up to larger selected strata but again compromises data depths as FADN misses crucial farm characteristics. Future research should focus on developing larger, representative farm samples with a high degree of detail to estimate the extent of the observed findings and gain more representativity.

5.3 Policy Implications

European countries have set ambitious goals to limit global warming to 1.5°C above pre-industrial levels, with the EU Green Deal committing to net-zero emissions by 2050 (European Commission, 2019). These efforts deeply impact the agricultural sector, which is crucial in reaching the set targets (Clark et al., 2020). Livestock production systems, especially cattle, are at the centre of action as they are an incremental contributor to agricultural emissions (Guyomard et al., 2021). Therefore, policymakers, researchers, and stakeholders in the European agricultural sector must understand and address these challenges.

Boix-Fayos et al. (2023) highlight the pivotal role of farmers as agroecosystems managers and ecosystem services providers in shaping more sustainable agriculture. This thesis aligns with this principle and delves into practical measures that can effectively reduce greenhouse gas emissions (GHG) at the farm level, using the dairy and dairy-beef farms in Norway as a case study. Here, feed optimisation, manure management, biofuels, and herd management can cut emissions by up to 20%, with some offering additional benefits such as reducing N losses through improved fertiliser efficiency.

However, the thesis also underscores the significant costs associated with these emission reduction measures, necessitating political intervention to implement them on a larger scale. Various policy tools can be employed, including market-based allocation through carbon trade, command-and-control measures that enforce specific technologies and practices, and information and support instruments that encourage desired behaviours. While carbon trading can effectively reduce emissions, it requires a reliable emission measurement system (Lengers et al., 2013; Stepanyan et al., 2023). However, establishing an EU-wide farm-level emission tracking system is still pending, and if implemented, it would involve substantial transaction costs. Moreover, simplified emission estimation might not capture low-cost abatement options, such as feed optimisation, as demonstrated in this thesis. While command-and-control policies or support schemes can directly regulate certain technologies (e.g., manure application technology), measures like herd management pose challenges in terms of control. Therefore, informing and educating farmers about low-emission farm management can serve as a bridge until emission estimation tools are ready for widespread application, thereby including the agricultural sector in established emission trading schemes.

Even when the assessed abatement measures are introduced on all farms, achieving net-zero emissions seems elusive (Rees et al., 2020; Duffy et al., 2022). Accordingly, some European countries are considering lowering emissions by reducing their active cattle herd (Jongeneel & Gonzalez-Martinez, 2021). This has also been found to be an ultimate measure to abate emissions in this thesis. This drastic step has led to farmers' protests, fearing high sunk costs from capital in production facilities. This thesis finds better environmental indicator scores for beef from dairy breeds than from specialised beef breeds, suggesting that herd size reductions should start there to have a bigger impact. Furthermore, mixed dairy-beef farms following profit maximising rationale cull the beef-producing animals before dairy due to the higher profitability of the latter, further hinting that beef production should be targeted first if herd reductions are pushed through. However, tinkering with the domestic supply and demand of meat and milk comes with its merits. It could lead to undesired market effects, like emission leakage (Zech & Schneider, 2019; Haddad et al., 2024). Carbon border adjustment measures (CBAM) are thought to circumvent this carbon leakage by taxation of goods imported into Europe based on the emissions associated with their production (Spiegel et al., 2024). However, the EU CBAM has not yet been extended to agricultural products.

Besides governmental climate action plans, European cattle farms are deeply intertwined with policies targeting and influencing different production dimensions. Many countries pay coupled support to farmers to prevent structural change, strengthen the sector, and stabilise farm income (Vinci, 2022). The practice is not only highly opposed due to its production-distorting nature but also due to the subsidisation of potentially unsustainable production systems. Furthermore, it can also hinder efficiency gains in production (Martinez Cillero et al., 2021). The EU Common Agricultural Policies's (CAP) direct payments under pillar I are non-coupled and, therefore, less distortive but still lack the consideration of sustainability (Beard & Schwimbank, 2001; Uthes et al., 2011; Scown et al., 2020).

Accordingly, compensating and rewarding farmers for their environmental actions are becoming more prominent in European countries. Agri-environmental schemes and the EU CAP's so-called “enhanced conditionality” try to bind payments to sustainable farming practices. This thesis identifies potential trade-offs between economic and environmental indicators when comparing farming systems, which must be addressed in the design of these schemes. In their current form, these schemes seem not to offset the contrasting policy goals of maintaining farm income and providing environmental benefits completely and, therefore, need refinement (Petsakos et al., 2023).

Further challenges for policy design arise when cattle production’s contributions to environmental impacts beyond GHG emissions are considered. This thesis estimates environmental indicators such as eutrophication, acidification, and particulate matter formation. The jointness of the multiple impacts can cause issues depending on the nature and direction of the relationship of the impacts. Some impacts may originate from similar sources. For example, eutrophication, particulate matter formation, and acidification are found to be caused by ammonia emissions (Velthof et al., 2012). Therefore, policies addressing these emissions can utilise synergies to tackle multiple targets. Conversely, other environmental impacts can have reciprocal relationships leading to trade-offs. For example, grazing cattle emit GHG emissions while preserving valuable habitats for biodiversity (Schils et al., 2022). Here, the degree of jointness, the occurrence of market failure, the magnitude of the impacts, and their regional scale must be considered to prioritise targets eventually (OECD, 2003). The issue extends when other production dimensions are considered, for example, social impacts or cattle production contributions to feed-food competition.

Policy reform seems inevitable due to persistent trade-offs between policy goals, impact categories, and schemes. Furthermore, changing societal expectations towards farmers, like animal welfare and consumer preferences for health and nutritional attributes of beef and dairy products, emerge as new tasks for decision-makers (Guyomard et al., 2021). The complexity of these tasks underscores the need to balance economic viability, environmental responsibility, and social ethics. A model-based holistic sustainability assessment following the LCA concept can guide these decisions, but the challenge remains large.

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Chapter 6
Appendix

6.1 Appendix Chapter 2

Table S1 Feed used to produce one kg of beef meat from young bulls per system Source: Own calculations based on model results

Feedstuff in kg FM kg meat^{-1}	BE	FR-IT	GE-GE
Grazed grass	44.617	38.151	
Gras silage	4.425	18.977	0.207
Maize silage	8.669	9.884	21.562
Wheat	3.520		0.462
Barley			0.291
Soybean meal		0.365	
Energy concentrate		1.092	
Protein concentrate		0.455	1.916
Beet pulp	18.080	2.983	
Milk	5.897	3.001	

Table S2 Parameter ranges of sensitivity analysis. [a] Factors are specific to systems that transfer calves. [b] Own calculation based on monthly prices for raw milk in Germany from 01/2010 to 06/2020. [c] Own calculation based on monthly prices for fodder wheat in EU from 01/2010 to 06/2020.

Parameter	Coefficient of variation (%)	Source
Weight at butchering [a]	1.92	(Gallo et al. 2014)
Age at butchering [a]	10.22	(Gallo et al. 2014)
Beef price	2.06	(Gallo et al. 2014)
Weight of weaned calves	6.82	(Gallo et al. 2014)
Price of replacement animals	4.48	(Gallo et al. 2014)
Maize yield	15	(Schils et al. 2018)
Grass yield	15	(Lorenz et al. 2020)
Milk price [b]	12	(EC 2020)
Concentrate price [c]	17	(EC 2020)

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Table S3 Regression output for Belgium system

	Dependent variable:									
	GWP	FEP	MEP	PMFP	TAP	FDP	CM	WT	PCE	CCE
Concentrate price	-0.018***	0.00000***	-0.00003***	0.00001	0.0002***	-0.0001	-0.0004***	-0.001***	0.002***	0.00000
	(0.001)	(0.00000)	(0.00001)	(0.00001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.00001)
Grass yield	0.031***	-0.00002***	-0.0001***	-0.00001	0.0003***	0.002***	0.001***	-0.001**	0.007***	0.001***
	(0.001)	(0.00000)	(0.00001)	(0.00001)	(0.0001)	(0.0001)	(0.0001)	(0.0003)	(0.0002)	(0.00001)
Maize yield	-0.033***	-0.00001***	-0.00005***	0.001***	0.004***	-0.013***	0.006***	0.012***	0.015***	-0.0002***
	(0.001)	(0.00000)	(0.00001)	(0.00001)	(0.0001)	(0.0001)	(0.0001)	(0.0003)	(0.0002)	(0.00001)
Animal weight	-0.179***	-0.00004***	-0.0003***	-0.001***	-0.003***	-0.001	0.033***	-0.036***	0.0003	0.0005***
	(0.011)	(0.00000)	(0.0001)	(0.0001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.0001)
Age at slaughter	0.018***	0.00001***	0.00002*	0.00001	0.0001	0.0003*	-0.002***	-0.002***	-0.001	-0.00004***
	(0.002)	(0.00000)	(0.00001)	(0.00002)	(0.0001)	(0.0002)	(0.0002)	(0.0004)	(0.0004)	(0.00001)
Beef price	0.139***	0.00003***	0.0002***	0.0002**	0.001***	0.003***	0.047***	0.019***	-0.003*	-0.0004***
	(0.011)	(0.00000)	(0.0001)	(0.0001)	(0.0005)	(0.001)	(0.001)	(0.002)	(0.002)	(0.0001)
Price of replacement animals	0.004	-0.00000	0.00002	0.00002	0.0001	0.00004	-0.031***	-0.0002	-0.0005	-0.00001
	(0.005)	(0.00000)	(0.00003)	(0.00005)	(0.0002)	(0.0003)	(0.0004)	(0.001)	(0.001)	(0.00003)
R^2	0.626	0.788	0.205	0.757	0.826	0.939	0.911	0.694	0.830	0.859
Adjusted R^2	0.623	0.787	0.199	0.755	0.825	0.939	0.911	0.692	0.829	0.858
Residual Std. Error (df = 992)	0.399	0.0001	0.002	0.004	0.018	0.028	0.036	0.075	0.066	0.002
F Statistic (df = 7; 992)	237.139***	527.489***	36.521***	441.428***	672.225***	2,192.029***	1,458.366***	321.279***	692.779***	864.016***

Note: *p<0.1; **p<0.05; ***p<0.01

Table S4 Regression output for French-Italian system

	Dependent variable:									
	GWP	FEP	MEP	PMFP	TAP	FDP	CM	WT	PCE	CCE
Concentrate price	0.007***	-0.00000	-0.00004***	-0.00000	0.00002	-0.0003***	-0.001*	0.002***	0.001***	0.0004***
	(0.001)	(0.00001)	(0.00001)	(0.00001)	(0.00004)	(0.0001)	(0.0003)	(0.0005)	(0.0001)	(0.0001)
Concentrate price*	-0.009***	-0.00000	-0.0001***	-0.00001	-0.0001	-0.001***	-0.002***	0.0003	0.002***	0.001***
	(0.001)	(0.00001)	(0.00001)	(0.00001)	(0.00004)	(0.0001)	(0.0003)	(0.0005)	(0.0001)	(0.0001)
Grass yield	0.032***	-0.0003***	-0.001***	-0.001***	-0.003***	0.003***	-0.0004	-0.006***	0.002***	0.001***
	(0.001)	(0.00001)	(0.00001)	(0.00002)	(0.00005)	(0.0001)	(0.0003)	(0.001)	(0.0001)	(0.0001)
Maize yield*	0.029***	0.00001	-0.0001***	-0.0001***	-0.0002***	-0.001***	0.006***	-0.001	0.0001	-0.001***
	(0.001)	(0.00001)	(0.00001)	(0.00002)	(0.00005)	(0.0001)	(0.0003)	(0.001)	(0.0001)	(0.0001)
Animal weight	-0.119***	-0.0002**	0.00001	-0.0001	-0.002***	0.001	0.036***	-0.038***	-0.003**	0.001***
	(0.011)	(0.0001)	(0.0001)	(0.0001)	(0.0004)	(0.001)	(0.002)	(0.004)	(0.001)	(0.0005)
Age at slaughter	0.003	0.00002	0.00000	0.0001***	0.001***	-0.001***	-0.018***	0.018***	0.002***	-0.002***
	(0.002)	(0.00002)	(0.00002)	(0.00002)	(0.0001)	(0.0002)	(0.0004)	(0.001)	(0.0002)	(0.0001)
Weight at transport	0.090***	-0.0002***	0.0001***	0.0002***	0.001***	0.001***	-0.029***	0.037***	-0.001***	-0.001***
	(0.003)	(0.00002)	(0.00003)	(0.00003)	(0.0001)	(0.0002)	(0.001)	(0.001)	(0.0003)	(0.0001)
Beef price	-0.022**	0.00002	-0.0001	-0.00003	-0.0004	-0.001	0.045***	0.005	0.001	0.0004
	(0.010)	(0.0001)	(0.0001)	(0.0001)	(0.0003)	(0.001)	(0.002)	(0.004)	(0.001)	(0.0004)
Price of replacement animals	0.113***	0.0002***	0.0001*	0.0002***	0.001***	0.001***	-0.024***	-0.001	-0.001	-0.00001
	(0.005)	(0.00003)	(0.00004)	(0.0001)	(0.0001)	(0.0003)	(0.001)	(0.002)	(0.0005)	(0.0002)
R^2	0.732	0.518	0.777	0.831	0.847	0.569	0.864	0.694	0.405	0.619
Adjusted R^2	0.729	0.513	0.775	0.830	0.845	0.565	0.863	0.691	0.400	0.615
Residual Std. Error (df = 986)	0.383	0.003	0.004	0.004	0.012	0.028	0.079	0.139	0.038	0.016
F Statistic (df = 9; 986)	299.053***	117.624***	382.277***	539.178***	604.166***	144.392***	694.833***	248.338***	74.646***	177.871***

Note: *p<0.1; **p<0.05; ***p<0.01

Table S5 Regression output for German system

	Dependent variable:									
	GWP	FEP	MEP	PMFP	TAP	FDP	CM	WT	PCE	CCE
Concentrate price	0.001	0.00000	0.00000	0.00000	0.00000	0.0001	0.0002*	-0.00000	0.00004	-0.00001
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0001)	(0.0001)	(0.0004)	(0.0001)	(0.00001)
Concentrate price*	-0.034***	-0.00000***	-0.0002***	0.00004***	0.0003***	-0.004***	-0.005***	0.010***	0.003***	0.0003***
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0001)	(0.0001)	(0.0004)	(0.0001)	(0.00001)
Grass yield	-0.001	-0.00000	-0.00000	-0.00000	-0.00002	-0.00002	0.0002	-0.0004	0.00002	0.00002**
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0001)	(0.0002)	(0.0005)	(0.0001)	(0.00001)
Maize yield	-0.0003	0.000	-0.00001	0.00000	0.00001	-0.0002	-0.0002	0.0004	0.00005	0.00000
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0001)	(0.0002)	(0.0004)	(0.0001)	(0.00001)
Maize yield*	-0.014***	-0.00001***	-0.0003***	-0.0002***	-0.001***	-0.001***	0.0004***	-0.006***	0.001***	0.0001***
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0001)	(0.0002)	(0.0005)	(0.0001)	(0.00001)
Animal weight	0.090***	0.00001***	0.001***	-0.0002***	-0.001***	0.011***	0.008***	-0.042***	-0.010***	-0.001***
	(0.008)	(0.00000)	(0.00005)	(0.00003)	(0.0001)	(0.001)	(0.001)	(0.004)	(0.001)	(0.0001)
Age at slaughter	-0.036***	-0.00000***	-0.0003***	0.0002***	0.001***	-0.006***	-0.002***	0.032***	0.007***	0.0003***
	(0.002)	(0.00000)	(0.00001)	(0.00001)	(0.00003)	(0.0002)	(0.0002)	(0.001)	(0.0001)	(0.00001)
Weight at transport	-0.004*	-0.00000***	-0.00002	0.00001	0.00002	-0.0003	0.0001	0.001	0.0005**	0.0001***
	(0.002)	(0.00000)	(0.00001)	(0.00001)	(0.00004)	(0.0003)	(0.0003)	(0.001)	(0.0002)	(0.00002)
Beef price	0.089***	0.00001***	0.001***	-0.0001***	-0.001***	0.011***	0.015***	-0.024***	-0.007***	-0.001***
	(0.008)	(0.00000)	(0.00004)	(0.00003)	(0.0001)	(0.001)	(0.001)	(0.003)	(0.001)	(0.0001)
Price of replacement animals	-0.021***	-0.00000***	-0.0001***	0.00002	0.0002***	-0.003***	-0.005***	0.007***	0.002***	0.0002***
	(0.004)	(0.00000)	(0.00002)	(0.00001)	(0.0001)	(0.0005)	(0.001)	(0.002)	(0.0003)	(0.00003)
Milk price	0.0001	0.00000	0.00001	0.00000	-0.00001	0.0001	-0.0002	-0.0002	-0.0001	-0.00000
	(0.001)	(0.00000)	(0.00001)	(0.00000)	(0.00002)	(0.0002)	(0.0002)	(0.001)	(0.0001)	(0.00001)
R^2	0.680	0.884	0.811	0.870	0.831	0.705	0.603	0.787	0.786	0.636
Adjusted R^2	0.676	0.883	0.808	0.869	0.829	0.702	0.598	0.785	0.784	0.632
Residual Std. Error (df = 988)	0.285	0.00002	0.002	0.001	0.005	0.037	0.041	0.120	0.026	0.002
F Statistic (df = 11; 988)	190.477***	687.307***	384.260***	601.357***	440.120***	214.864***	136.211***	331.965***	330.083***	156.855***
Note:										*p<0.1; **p<0.05; ***p<0.01

Table S6 Literature review

Study	Region	Scope	FU	GWP	TAP	FEP	MEP	FDP	CM	HCP
Our study	Belgium, France, Italy, Germany	Dairy & suckler beef, cradle to farm gate	kg beef meat carcass weight	12.0-32.3 kg CO_2eq	0.14-0.40 kg SO_2eq	1.33-6.78 g Peq	26.3-48.6 g Neq	0.23-0.48 kg oileq	0.03-0.39 €	0.29-0.66
Nguyen et al. (2010)	EU	Dairy & suckler beef, cradle to farm gate including land use change	kg beef meat slaughter weight	16.0-27.3 kg CO_2eq	101-210 g SO_2eq	-	622-1651 g NO_3eq	41.3-59.2 MJeq	-	-
Hammar et al. (2022)	Uppsala County, Sweden	Suckler beef, cradle to farm-gate including soil organic carbon	kg bone free beef	23-27 kg CO_2eq	-	-	-	-	-	-
Huerta et al. (2016)	Veracruz, Mexico	Beef production from dairy calves, farm production to prior to transport for consumer consumption	kg of boneless & fat-less beef.	21.7-20.6 kg CO_2eq	0.57-0.79 kg SO_2eq	0.49-0.36 kg Peq	0.032-0.036 kg Neq	-	-	-
Kamilaris et al. (2020)	Scotland, Great Britain	Steers & heifers, gate to gate, finishing stage only	kg life weight	7-22 kg CO_2eq	-	-	-	-	-563-£169 per animal	-
Bragaglio et al. (2018)	Italy	Extensive & intensive beef cattle systems, cradle-to-farm gate	kg live weight of marketed beef cattle	17.62-26.30 kg CO_2eq	0.20-0.30 kg SO_2eq	-	779.17-1009.20 g NO_3eq	-	-	0.17-0.44[a]

Wiedemann et al. (2015)	Australia	Beef & lamb, at the regional storage center in the USA	kg of retail ready cuts	16.1-27.2 kg CO_2eq	-	-	-	28.1-46.6 MJeq	-	0.3-7.9[a]
van Selm et al. (2021)	New Zealand	Current beef production system & conversion to dairy beef only	Kg carcass weight	21.3-16.7 kg CO_2eq	-	-	-	-	-	-
Angerer et al. (2021)	South Tyrol, Italy	Organic &conventional dairy- & beef breed beef production, cradle-to-farm gate	kg of live weight (LW) beef cattle marketed	17.1-32.7 kg CO_2eq	9.3-32.5 g SO_2eq	2.8-8.6 g PO_4eq	-	13.8-48.8 MJeq	-	-
Florindo et al. (2017)	Mato Grosso do Sul State, Brazil	Beef cattle from cradle to the farm gate	kg of live weight at the farm gate	17.5-31.2 kg CO_2eq					0.6-0.7 US$ per FU	
Veysset et al. (2010)	Charolais area, France	Beef cattle farms	t live weight	14.3-18.3 t CO_2eq				26.4-31.9 MJeq	566-685 Bovine gross margin €/LU[b]	

[a] protein content of the meat yield weight by human edible protein in feed consumed by the animals; [b] Livestock unit

Table S7 Abbreviation table

Abbreviation	Definition
BE	Belgium system
BE-BF	Belgium breeder and fattener farm
CH_4	Methane
CM	Contribution margin
ESM	Electronic Supplementary Material
EU	European Union
FDP	Fossil fuel depletion potential
FEP	Freshwater eutrophication potential
FR-IT	French-Italian system
FR-IT-B	French breeder
FR-IT-F	Italian Breeder
FU	Functional unit
GE-GE	German system
GE-GE-B	German dairy farm
GE-GE-F	German fattener farm
GHG	Greenhouse gas
GWP	Global warming potential
HCC	Human-consumable calories
HCP	Human-consumable protein
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment

MCDM	Multi-criteria decision-making
MEP	Marine water eutrophication potential
N	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_3-	Nitrate
NO_x	Nitrogen oxides
P	Phosphorus
$PM_{2.5}$	Particulate matter emission
PMFP	Particulate matter formation potential
SLCA	Social Life Cycle assessment
TAP	Terrestrial acidification potential
WT	Working time

6.2 Appendix Chapter 3

Table A1 Description of the methodology for GHG emission evaluation for each source and pollutant.

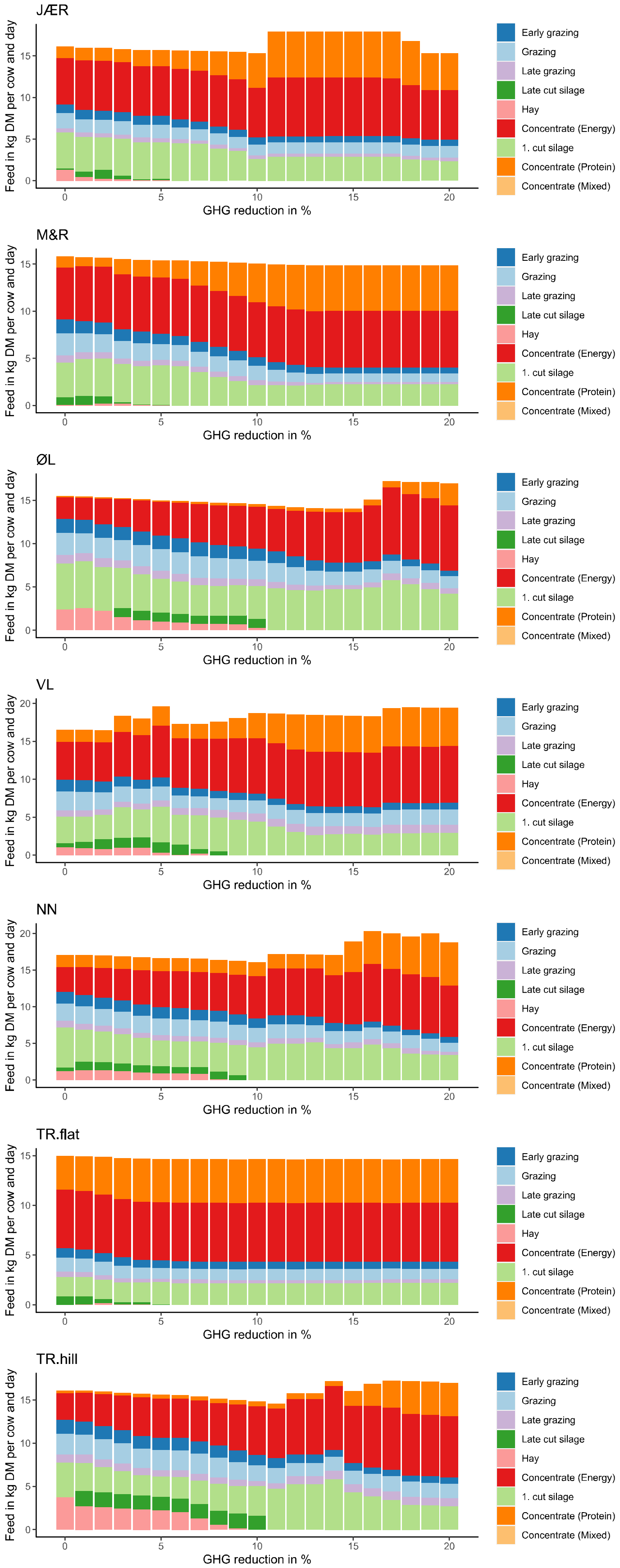
Source/Sub-source	Pollutant	Methodology	Tier
Enteric fermentation	CH_4	IPCC (2019)	2
Manure management	CH_4	IPCC (2019)	2
	NH_3, N_2O, NO_x, N_2	EEA (2016)	2
	Particulate matter	EEA (2013)	2
Pasture	CH_4	IPCC (2019)	2
	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field and pasture/manure application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field and pasture/ fertilizer application	NH_3	EEA (2016)	2
	N_2O, NO_x, N_2	IPCC (2019)	1
Field/lime application	CO_2	IPCC (2019)	1
Field/crop residues	N_2O, N_2	IPCC (2019)	1
Field	Particulate matter	EEA (2016)	1
Field and pasture	NO_3^-	Richner (2014)	
	P	Prasuhn (2006)	
Indirect N_2O	N_2O	IPCC (2019)	1

Table A2 Economic and social results for the farm of interest in each scenario.

	BE			FR-IT			GE		
	Base	**FRG**	**SR**	**Base**	**FRG**	**SR**	**Base**	**FRG**	**SR**
Revenues (k EUR)	307	318	418	113	113	121	792	800	812
Beef (k EUR)	201	201	285	69	69	79	125	125	142
Crop (k EUR)	53	64	98				260	267	263
Subsidies (k EUR)	52	52	35	44	44	42	56	56	56
Variable costs (k EUR)	104	106	157	22	21	18	270	269	273
Buy cost (k EUR)	55	54	111	11	10	8	143	144	148
Feed (k EUR)	22	20	33	5	5	2	33	34	37
Profit (k EUR)	169	178	217	71	74	85	391	401	407
Prod HEP (kg)	13,812	17,715	29,632	1926	1926	2141	76,081	79,267	76,916
Animal (kg)	6906	6906	15,217	1926	1926	2141	36,702	36,702	35,895
Productivity (kg/ha)	115	147	243	20	20	22	281	292	282

6.3 Appendix Chapter 4

Plot A1 Average daily ration of the dairy cows in kg dry matter (DM)



Plot A2 Average annual amount of manure applied in m^3

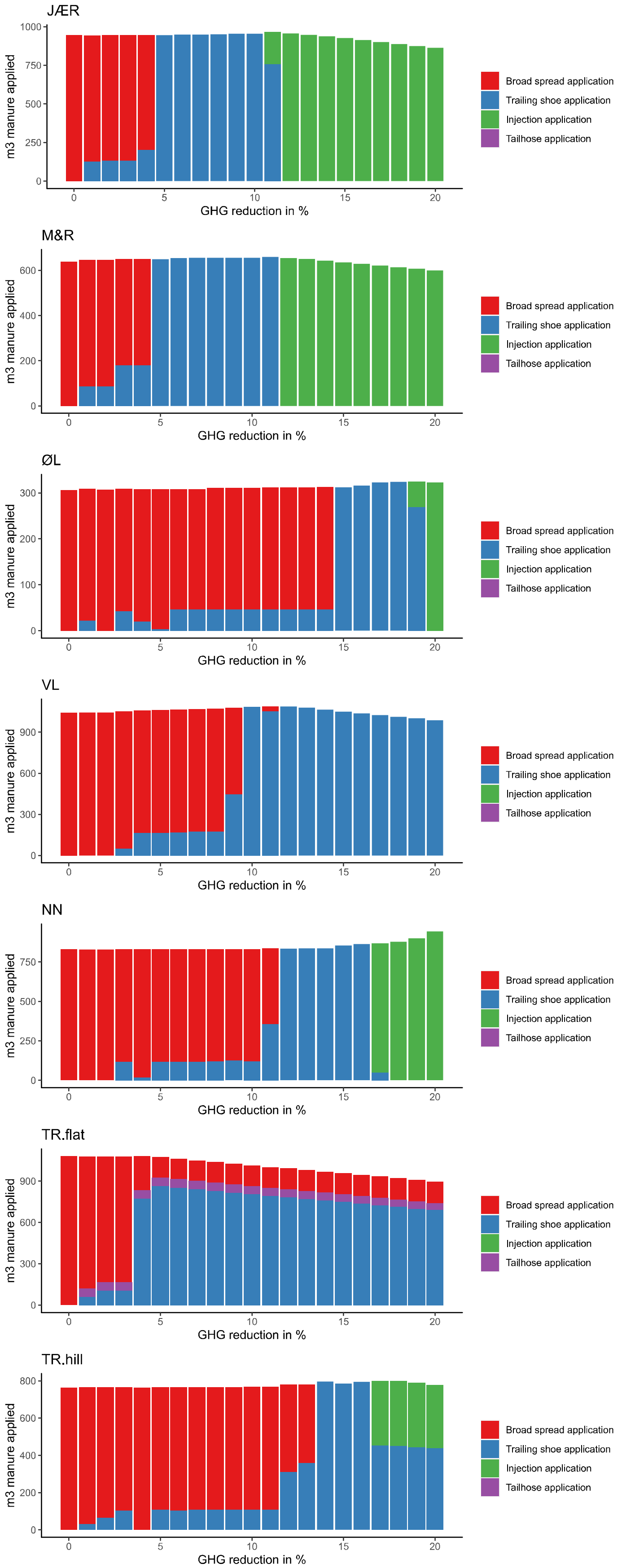


Table T1 Literature overview

Study	Region	Scope	Approach	Abatement costs	Abatement strategies
Our study	Norway	Typical dairy farms from FADN	Bio-economic optimisation model FarmDyn	1-5% GHG emissions abatement possible on some farms under 2000 NOK per t CO_2eq	Feed optimisation towards energy-rich ration, low-emission manure application technology, biodiesel, herd size reduction
Mosnier et al. (2019)	France	Single dairy farms and the whole sector	3 supply side models & 1 partial equilibrium model	1-6% GHG emissions abatement can be achieved at around 20€ per t CO_2eq	Animals reach their full production potential & moderately intensive land management
Lengers et al. (2014)	Germany	Single dairy farm level	Bio-economic optimisation model FarmDyn, meta-modelling	MAC strongly increase beyond a 1–5% reduction, depending on farm attributes and used indicators. MAC decrease rapidly with farm size	
Cecchini et al. (2018)	Umbria (Italy)	10 dairy cattle farms	Slacks-Based Measure-Data	Average abatement cost of € 243.08 in terms of lower milk	

			Envelopment Analysis (SBM-DEA)	production per ton of CO_2eq reduced	
Wettemann et al. (2017)	Germany	216 dairy farms in northern Germany	Data Envelopment Analysis	Abatement cost of about €165 per t CO_2eq via a switch from cost-efficient to GHG-efficient farming	Reductions in nitrogen use, an extension of diesel use, higher share of legumes and a longer effective lifetime of cows.
Duffy et al. (2021)	Costa Rica	Ninety dairy farms	Combination of literature review & expert judgement to assess mitigation potential	Marginal abatement costs between -0.64 and 1.38 USD per kg milk depending on measures and farms	Measures that improve animal health & increase pasture quality, replacement of lower quality by-product feeds with high quality concentrate feed