Mind Over Metrics:

The role of indicators in mitigating the environmental impacts of ruminant agriculture

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“What is the use of a house if you haven’t got a tolerable planet to put it on?”

Henry David Thoreau (1860)

In loving memory of my grandfather,

LAWRENCE P. WACHLER

He didn’t believe in climate change,

but he believed in me**.**

Acknowledgements

I have written this thesis through a very dark chapter in the history of my country and, indeed, the world. Trying to build a brighter future is not easy when it seems that, now more than ever, the powers that be are working against us. However, the following individuals give me hope that tomorrow will be a better day.

I first thank Myles Allen for opening the door to this opportunity, for the reminder that what I have to say matters, and for always pushing me to be the best scientist I can be. I thank Harriet Bartlett for being an incredible role model, and for supporting me when I need it most. I also thank Tim Searchinger for teaching me that there really is no free lunch. And of course, I thank Geoffrey Biscuit for his invaluable contributions to my supervision meetings.

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Thank you to my brilliant husband, Ben, who I married halfway through the DPhil in the Botanic Gardens. Oxford will always be our city, but bigger adventures await.

Finally, I thank my parents, who have always supported me from oceans away, and my little brother Jake, who I think is the proudest of me, though he'd never say it out loud.

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Abbreviations

3-NOP: 3-nitrooxypropanol
AFOLU: Agriculture, forestry, and other land uses
AHDB: Agriculture and Horticulture Development Board
CAP: Common Agricultural Policy
CCC: Climate Change Committee
CO_2: Carbon dioxide
CO_2-e: Carbon Dioxide Equivalents
CO_2-we: Carbon Dioxide Warming Equivalents
COC: Carbon Opportunity Cost
CSRD: Corporate Sustainability Reporting Directive
DACCS: Direct Air Carbon Capture and Storage
DEFRA: Department for Environment, Food & Rural Affairs
dLUC: Direct Land Use Change
DoAFM: Department of Agriculture, Food and the Marine
ELMs: Environmental Land Management schemes
EU: European Union
EUDR: European Union Deforestation Regulation
FaIR: Finite-amplitude Impulse Response
FAO: Food and Agriculture Organization
FarmPET: Farm Productivity Evaluation Tool
FCE: Feed Conversion Efficiency
GHG: Greenhouse Gas
GHGP: Greenhouse Gas Protocol
GTP: Global Temperature-change Potential
GWP: Global Warming Potential
HFG: Hilton Food Group
iLUC: Indirect Land Use Change
IPCC: Intergovernmental Panel on Climate Change
ISO: International Organization for Standardization
LCA: Life Cycle Assessment
LULUCF: Land Use, Land Use Change, and Forestry
ONZ: Oxford Net Zero
NIR: National Inventory Report
NPP: Net Primary Productivity
PEM: Production Emission
SBTi: Science-Based Targets initiative
sLUC: Statistical Land Use Change
UNEP: United Nations Environment Programme
UNFCCC: United Nations Framework Convention on Climate Change
WBCSD: World Business Council for Sustainable Development
WRI: World Resources Institute

Abstract

This thesis investigates the role that environmental indicators play in the development and execution of climate mitigation strategies for the agriculture sector with a focus on ruminant livestock in Europe. This project sits at the nexus of climate science and environmental policy, applying both qualitative and quantitative methods across three papers. While there are a range of environmental impacts associated with agricultural production, I focus on greenhouse gas emissions resulting from the ruminant production system itself, and the climate effects of land use and land use change.

The motivation for this research came from my time working at the World Resources Institute as part of the secretariat for the Greenhouse Gas Protocol's Land Sector and Removals Guidance and Standard. In my role as a facilitator of the Technical Working Group consisting of mainly corporate stakeholders, I came to understand the obstacles faced by companies with land-based product emissions in their supply chains. I also developed appreciation and sympathy for those companies who nevertheless try to make a meaningful contribution towards solving the climate crisis. As such, my thesis will explore the issues associated with reporting and mitigating the environmental impacts of ruminant agriculture and will offer new insights on how different stakeholder groups can better align objectives and actions to design more effective strategies moving forward.

In the first paper, I estimate greenhouse gas emissions and land use associated with cattle production in the UK and project four future mitigation scenarios. These scenarios, which range from business-as-usual to the full-scale implementation of multiple experimental technologies,

are measured using several different indicators and analyzed based on the policy incentives of each set of indicators.

The second paper explores the potential climate consequences of the UK's new Environmental Land Management schemes, which incentivize on-farm interventions that may affect domestic outputs of ruminant products and feed crops. I introduce a new tool developed for this paper that calculates the carbon benefits of emissions reductions and/or carbon storage relative to the carbon opportunity costs of offshored food production.

The final chapter takes a qualitative approach, using stakeholder and expert interviews to develop a conceptual understanding of what 'net zero' means to corporate, academic, government, and farmer groups across the European agricultural policy sphere and supply chain. This chapter uses stakeholder perspectives to ultimately identify opportunities to foster collaboration across the ruminant sector in the ongoing effort to improve the sustainability of ruminant production.

Through this interdisciplinary approach, I present both qualitative and numerical evidence that the choice of metric or the target label is far less important than the tangible outcomes that result from decisions made. I have found that stakeholders across the ruminant sector feel as though debates around metrology distract from what can and should be done to make meaningful progress on the complex issue of feeding a growing population within planetary boundaries. Rather than continuing the cycle of developing mitigation strategies based on emissions accounting conventions and targets which fail to facilitate sufficient and timely action, I propose we work backwards. We must instead select indicators and set targets based on their ability to incentivize progress towards the global objectives for the food system, such as minimizing further warming and native ecosystem loss. In other words, we must put Mind Over Metrics.

Overview

This thesis contains the following structure:

Chapter 1 outlines the research aims and questions driving the thesis.

Chapter 2 provides a review of existing literature to justify the novel contributions made by this thesis. Topics include scientific background on greenhouse gas emissions accounting, debates around land use metrics, technical discussions regarding agricultural mitigation interventions, and context on European land use policy.

Chapter 3 describes the research paradigm and justifies the methods used in the thesis, including statements on ethics and positionality.

Chapter 4 presents the findings of a scenario analysis of possible mitigation futures in the UK cattle sector as a means to explore the implications of various environmental metrics and the interventions they incentivize.

Zionts, Jessica, Harriet Bartlett, Tim Searchinger, and Myles Allen. 2025. "The Utility of Novel Environmental Impact Metrics in UK Ruminant Mitigation." *Environmental Research: Food Systems* 2 (2): 025009. https://doi.org/10.1088/2976-601x/add93e.

Chapter 5 introduces a new Excel tool (the Farm Productivity Evaluation Tool, FarmPET) which calculates the net climate costs or benefits of various on-farm interventions when considering the carbon opportunity costs of possible yield gains or losses and resulting global effects on food production in the context of ongoing UK farm subsidy policy debates.

Zionts, J., Bartlett, H., Searchinger, T., Allen, M. (n.d.). "Integrating the carbon opportunity cost into farm subsidy schemes." Under review in *Carbon Balance & Management*.

This paper was presented at the Global Land Programme's Open Science Meeting (November 2024, Oaxaca, Mexico) and the Livestock, Environment and People (LEAP) Conference (April 2025, Oxford, UK).

Chapter 6 is a qualitative analysis of perspectives on what net zero means for European ruminant agriculture, given differing assumptions about system boundaries, time horizons, and considerations of land use. Stakeholders consulted included policymakers, researchers, corporate representatives, and farmers.

Zionts, J., Bartlett, H., Allen, M. (n.d.) "Aligning corporate and national definitions of net zero for effective livestock mitigation policy in Europe." Under review in *Climatic Change.*

Chapter 7 provides a discussion of the main findings, offers answers to the research questions of the thesis, and highlights how the research constitutes new knowledge as a contribution to the literature. The final section of this chapter offers concluding remarks and proposes a new paradigm for corporate and national entities' approach to measuring and mitigating environmental impacts from the livestock sector.

Chapter 1: Introduction

This chapter provides context for the thesis, which can be succinctly summarized as the ways in which actors across the livestock sector measure the land use and climate impacts of agriculture, and how decisions around metrics inform direction for national and corporate mitigation strategies.

1.1 The (mis)alignment of agricultural mitigation strategies

Article 2 of the 2015 Paris Agreement lays out a global objective in battling climate change. Together, we must:

> *"[Hold] the increase in the global average temperature to well below 2° C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5° C…"* (UNFCCC 2015)

With global consensus that future warming must be limited, all greenhouse gas (GHG)-emitting sectors and member-states must develop and pursue strategies that contribute to this objective. This thesis explores the climate impact of the ruminant livestock sector and debates around its potential role in meeting the Paris Agreement target.

The global food system must address multiple challenges in tandem, which include feeding a growing population, reducing emissions in line with the Paris Agreement, and halting native ecosystem loss due to expansion of agricultural land (Searchinger et al. 2019; Gerten et al. 2020; Campbell et al. 2017). Based on institutional buy-in to target-setting and emissions-reporting guidance, there appears to be broad agreement among corporate stakeholders in agri-food supply chains that these impacts must be mitigated (Anderson et al. 2022; WRI and WBCSD 2022a).

However, there is no silver bullet for this complex problem. Rather, it requires a careful orchestration of multiple technological interventions, national policies, corporate cooperation, and behavioral shifts, as well as consideration of values that are less easily quantifiable such as animal welfare or biodiversity (Zurek et al. 2022). Thus, this thesis explores what these paths forward might be, for whom, and how targets should be set for companies and countries alike.

Cattle reared to produce beef and dairy account for a significant proportion of the global environmental impacts of agriculture (Steinfeld et al. 2006; Ritchie et al. 2022). Specifically, livestock emit approximately 32% of anthropogenic methane, most of which comes from cattle (UNEP 2021), and account for 80% of agricultural land use for both grazing and the production of feed (Ritchie and Roser 2019).

Article 4 of the Paris Agreement offers some guidance on how 2°C of warming can be avoided. It states that parties must:

> *"Achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century…"* (UNFCCC 2015)

In fossil-based sectors such as transportation or energy where the majority of the emissions come from carbon dioxide (CO_2), this balance would logically translate into a shift towards renewable sources of energy (Rockström et al. 2017; Rogelj et al. 2015), and potentially direct air-capture and carbon storage (DACCS) for hard-to-abate CO_2 emissions if the technology becomes scalable and cost-effective (Allen, Friedlingstein, et al. 2022; Fankhauser et al. 2022). Some also argue that 'removals by sinks' implies a need for negative emissions technologies or increased biological sequestration (Griscom et al. 2017; S. Smith et al. 2024).

In these sectors, the challenge centers on balancing emissions of carbon dioxide with removals of carbon dioxide; like-for-like. I recognize that this is complicated by an increasing focus on counteracting the emissions from fossil fuel-based activities with biological removals, which is not like-for-like. For agriculture, however, the calculus is even less clear. Ruminant agriculture drives climate change primarily through two processes; the emission of GHGs associated with raising animals, which mainly consist of methane and nitrous oxide, and the depletion of the terrestrial carbon sink through the clearing of native ecosystems for pasture or cropland for animal feed. In both cases, the allocation of responsibility of the livestock sector to meet the goals of the Paris Agreement and the mitigation efforts that should be pursued as a result have been the subjects of significant debate.

The controversy around methane relates to how its short-lived nature is considered (Meinshausen and Nicholls 2022; Allen et al. 2018). There is also disagreement around the framing of land use for meeting humanity's material needs while driving action to remain within biophysical planetary boundaries (Loconto et al. 2020). In the past decade, novel metrics have emerged to quantify these ruminant-specific impacts, which deviate from conventional methods and metrics of agricultural life-cycle assessment (LCA) (Allen et al. 2016; Searchinger et al. 2018).

These developments have given rise to questions around which accounting conventions are most appropriate at the national scale and within corporate supply chains where agricultural emissions are upstream (Scope 3). There is speculation that corporate or national entities seek to utilize metrics that align with their pre-conceived notions about what 'sustainable' agriculture should look like, or that might enable more easily-achievable targets (Cusworth et al. 2023; Garnett et al. 2017). As a result, there is an opportunity to study the extent to which metric choice can — and does — influence decision-making in the context of agricultural mitigation strategies.

In several European countries, emerging agricultural mitigation strategies focus on afforestation and shifting to low-input farming practices, often at the expense of livestock production (CCC 2025; DoAFM 2024; Minasny et al. 2017). When using conventional metrics with a national system boundary (which does not include the impacts of imported goods), this strategy provides a feasible trajectory to climate neutrality or "net zero" because some food production is offshored. However, given the global nature of both the food system and its impacts on the environment, I question whether solutions framed in this way can deliver a just food future and simultaneously contribute to the targets of the Paris Agreement.

Thus, this thesis focuses on the two main drivers of climate change in the ruminant livestock sector—production emissions and land use change—and explores how decisions around metrics and system boundaries influence incentives to mitigate the impact of producing meat and dairy.

1.2 Research questions

This research is driven by the high-level question of what can and should be done about the environmental impacts of agriculture at farm, corporate, and national scales, and the role that choices around environmental indicators play in the development of those mitigation strategies. The three chapters of original research apply a range of methods to explore the quantitative effects of metric choice, and the qualitative reality of how these topics are conceptualized by stakeholders across the agri-food landscape. When combined, this thesis offers practical insights into how companies and countries alike can develop climate strategies for the livestock sector in a more effective way. In approaching this subject, I acknowledge the need for cross-cutting solutions that encourage a focus on the shared global objective of *feeding the world without destroying it.*

Guiding the delivery of these aims are three central research questions:

Question 1: In what ways can metric choice for GHGs and land use influence mitigation priorities in the context of the UK cattle system? (Chapter 4)

Question 2: How might UK farm subsidies affect the productivity of domestic agriculture in the absence of large-scale diet changes, and how can we estimate the net global impact of these decisions? (Chapter 5)

Question 3: How do understandings of climate neutrality or net zero in the livestock sector differ across stakeholder groups in the context of European ruminant systems? (Chapter 6)

a. To what extent are these definitions influenced by what mitigation opportunities are feasible for a given stakeholder?
b. What are the socio-political obstacles (and opportunities) to reducing the environmental impacts of ruminant agriculture?

There is an additional, higher-level, question that this thesis does not directly answer but rather provides preliminary insights. Global targets have been set around emissions and warming (i.e. the Paris Agreement), and land use change. Yet, globally, progress on these targets is severely lacking. Therefore, I ask: *To what extent is exclusive reliance on conventional indicators hindering progress?* This question came about through the process of conducting the research for this thesis, and it is considered a critical theme for future studies.

1.3 Research outputs

Based on the research questions and aims presented in Chapter 1.2, I present the following diagram in Figure 1. 1. It illustrates how the concepts explored in this thesis relate to one another, and where each of the three empirical papers lie relative to the conceptual framing.

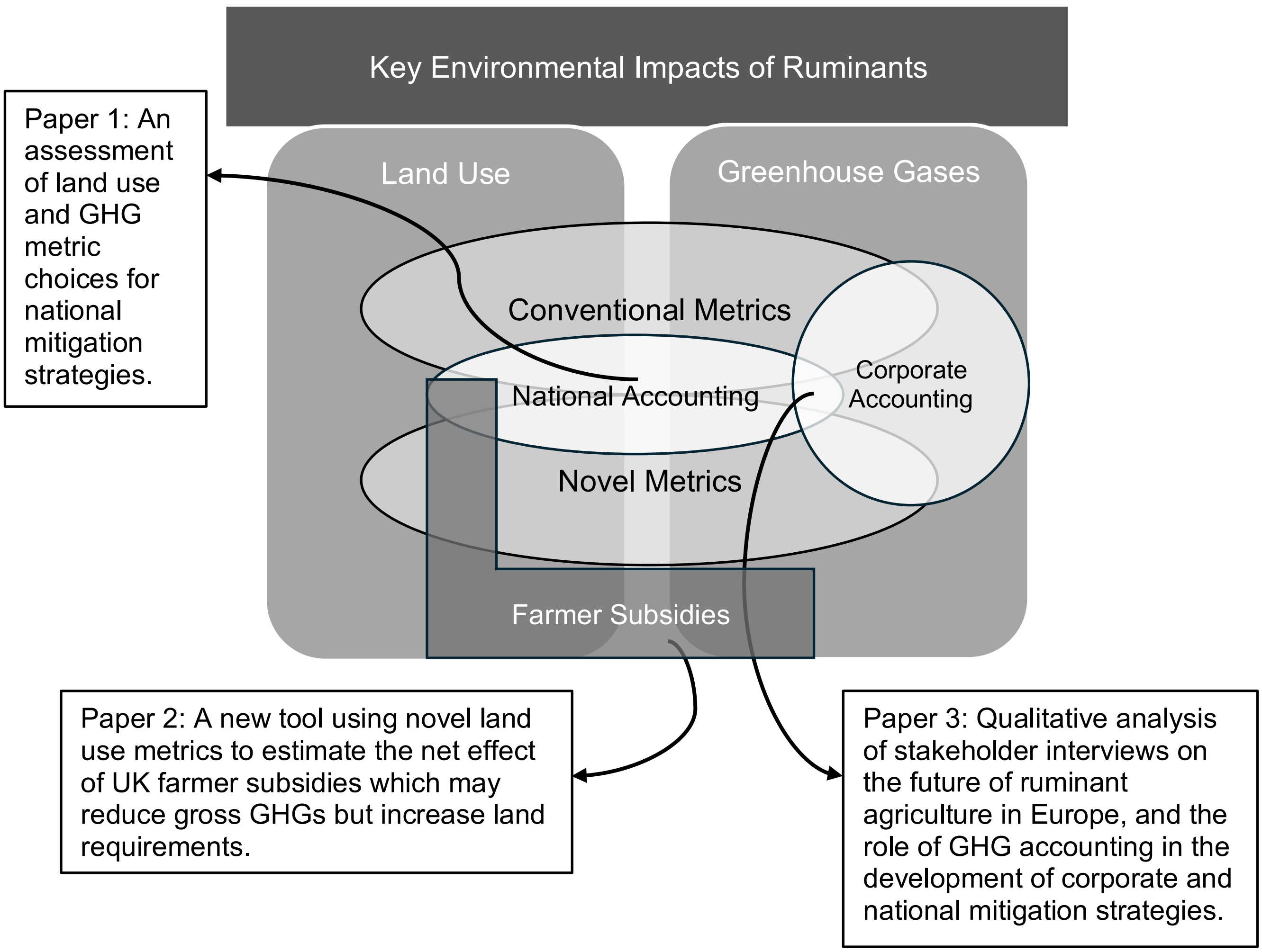

Figure 1. 1 Conceptual diagram of the key topics studied in this thesis, and how they relate to the three research chapters. The shapes describe how the concepts are used in my papers. Paper 1 focuses on national accounting of land use and GHG emissions using both conventional and novel metrics. Paper 2 looks at the use of novel land use metrics in the context of assessing farm subsidies. Paper 3 explores how GHG metric choice and definitions of net zero differ between national and corporate contexts.

To summarize, Paper 1 (Chapter 4) explores the implications of both conventional and novel metrics for GHGs and land use in the context of UK beef and dairy production. I apply different combinations of metrics under four future scenarios ranging from business-as-usual to the highly optimistic use of breakthrough technologies. Paper 2 (Chapter 5) delves deeper into the use of novel land use metrics in the context of emerging UK farmer subsidies that prioritize on-farm biodiversity and gross national emissions reductions, possibly at the expense of domestic food production. In this study, I develop a simple calculator that quantifies the trade-offs between domestic emissions reductions and removals, and land use change emissions overseas to compensate for reduced productivity. Lastly, Paper 3 (Chapter 6) uses data collected through 41 semi-structured interviews to understand the range of stakeholder perspectives on ruminant mitigation, and how feelings towards GHG metrics influence views on target setting and mitigation responsibility. In this analysis, I focus on the many ways the concept of net zero has been interpreted in the context of national and corporate mitigation strategies.

While the three papers utilize very different methods, they build on one another with the objective to provide policy-relevant insights at both national and corporate levels. As such, Table 1. 1 summarizes the three research outputs in terms of the questions they address, and how they relate to one another.

Table 1. 1 Description of each paper, the research questions, and connections with the other papers to demonstrate the cohesiveness of effort and intention across the three distinct approaches.

Paper/Chapter	Summary	Research Question(s)	Connections with other Papers
Paper 1/ Chapter 4	An assessment of land use and GHG metric choices for national mitigation strategies.	In what ways does metric choice for GHGs and land use influence mitigation priorities in the context of the UK cattle system?	This paper demonstrates which interventions are incentivized by which metrics, which serves as a quantitative basis for interviews in **Paper 3**.
Paper 2/ Chapter 5	A new tool using novel land use metrics to estimate the net effect of UK farmer subsidies which may reduce gross GHGs but increase land requirements.	How might UK farm subsidies affect the productivity of domestic agriculture, and how can we estimate the net global impact of these decisions?	**Paper 1** uses stylized scenarios and quantifies how novel land use metrics incentivize improved productivity. This paper explores that concept further through application to real UK farm subsidy policy. Stakeholder valuation of productivity compared to nature-forward farming provided framing for the interviews in **Paper 3**.
Paper 3/ Chapter 6	Qualitative analysis of stakeholder interviews on the future of ruminant agriculture in Europe, and the role of GHG accounting in the development of corporate and national mitigation strategies.	How do understandings of climate neutrality or net zero in the livestock sector differ across stakeholder groups in the context of European ruminant systems? a. To what extent are these definitions influenced by what mitigation opportunities are feasible for a given stakeholder? b. To what extent do stakeholder motivations and values influence conceptualizations of a sustainable system?	The insights drawn from the modeling exercises in **Papers 1 and 2** are assessed relative to how stakeholders in the agriculture sector conceptualize the issue of ruminant mitigation. This is a necessary step to bridge the gap between quantitative analysis and palatable policy recommendations.

Chapter 2: Literature review

This thesis explores environmental impact metrics and how they are used to make decisions. As stated in the Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report, *"no single metric is optimal for all policy goals"* (IPCC 2014). However, through the course of writing this thesis, I have found that stakeholders in the climate sector at large are distanced from the history of how certain metrics came to play such powerful roles in climate policy. As a result, there is a need to critically reexamine these emissions accounting conventions by questioning how useful they are for decision-making in the context of ruminant sector mitigation. Through this literature review, I revisit the scientific foundations of these metrics and trace the resulting debates and applications over the last few decades with a specific focus on greenhouse gas (GHG) and land use metrics.

The tensions at play are aptly framed by the distinction between 'attributional' versus 'consequential' emissions accounting. Attributional accounting is typically used for product footprints or annual inventories and quantifies the emissions *attributable* to an entity, whether corporate or governmental, over a given period. Consequential accounting, on the other hand, measures the emissions that occur as a result of a decision or intervention compared to a counterfactual baseline. Attributional inventories, which are typically used by decision-makers, are agnostic to what has occurred in the past or what might happen in the future. Given the lack of consideration for the future, I argue that these frameworks are at least partially responsible for society's failure to incentivize a level of mitigation necessary to effectively address future climate change. Consequential accounting, which considers the future by definition, can be problematic when used in an inventory setting, as I discuss throughout the literature review. In this thesis, I view attributional accounting as a necessary approach to annual inventories, but any question which is forward-looking, as most questions about climate mitigation are, must also consider consequential accounting. Approaches to emissions accounting, therefore, must enable both attributional and consequential reporting.

While there are active debates about which metrics should be used, there is still an important question as to why these arguments about metrics are happening in the first place. Environmental metrics have come to serve as a mechanism for the allocation of blame or responsibility to act. Thus, actors favor the accounting decisions that allocate them the least responsibility. The title of this thesis, Mind Over Metrics, is a nod to my overarching argument that, rather than accepting conventional metrics as given, or seeking the metrics which minimize responsibility, we must instead value a metric based on the role it can play in incentivizing action towards global objectives *moving forward.*

2.1 A brief introduction to climate change

The IPCC Special Report on 1.5°C defines climate change as "a change in the state of climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period…due to natural internal processes or external forcings" (IPCC 2018). Alternatively, the United Nations Framework Convention on Climate Change (UNFCCC) defines it as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability" (United Nations 1992). The former definition centers the physical reality and its measurability, while the latter focuses on changes that are attributable to human activity. In the

Anthropocene, however, greenhouse gas emissions are the driving force behind this 'change' under both definitions.

Greenhouse gases drive the observable phenomenon of a changing climate by causing perturbations in the radiative energy budget of Earth's climate system, known as radiative forcing (measured in Watts per square meter) (J. T. Houghton 2001). According to the IPCC, radiative forcing is defined as follows:

> *"The change in the net…radiative flux at the top of atmosphere due to a change in an (external) driver of climate change, such as a change in the concentration of carbon dioxide, the concentration of volcanic aerosols or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium."* (IPCC 2021a)

Radiative forcing is the direct consequence of a change in the composition of GHGs in the atmosphere, and is a driver of surface temperature change (Keith P. Shine 2000). Different GHGs have different properties, including the amount of radiative forcing they generate and the length of time over which the forcing occurs. Impulse response functions describe the radiative forcing over time for a single pulse of a greenhouse gas, but account for biogeochemical interactions such as ocean absorption of CO_2 as well (Joos et al. 2013). Figure 2. 1 shows the impulse response functions over time of different GHGs (left), and the resulting impact on temperature (right), highlighting the differences in how they behave in the atmosphere (IPCC 2013; Pierrehumbert 2014). The GHGs shown in the figure are carbon dioxide (blue), and two hypothetical short-lived GHGs that differ in terms of their half-lives and peak radiative forcings shown in green and red.

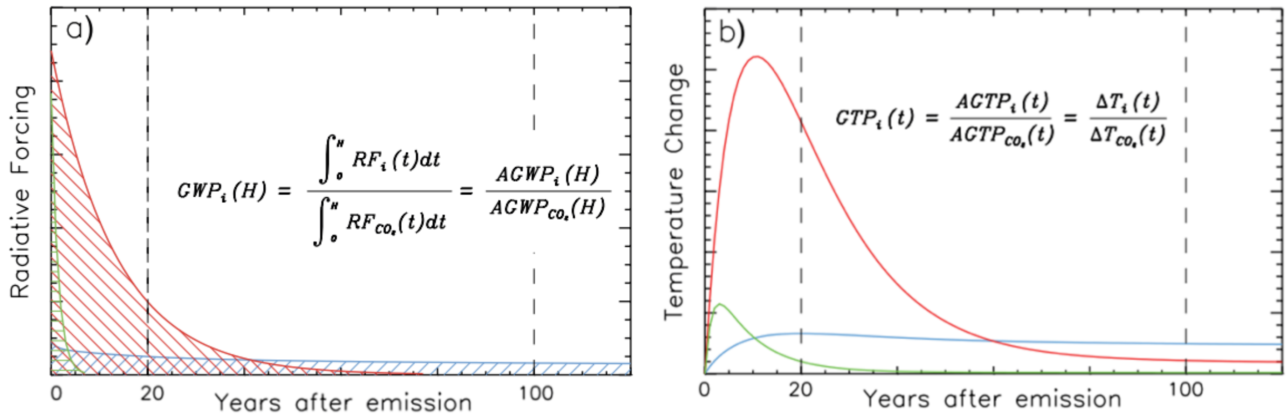

Figure 2. 1 Radiative forcing (a) and temperature change (b) from pulse emissions of CO_2 (blue), and two hypothetical short-lived GHGs (red and green) over time. While the short-lived gases significantly affect temperatures for a few decades, their radiative forcing quickly reduces to zero. Carbon dioxide, on the other hand, persist in the atmosphere for many centuries. Global Warming Potential is calculated as the radiative forcing of a greenhouse gas integrated over a given time horizon relative to that of carbon dioxide, as shown in the left panel The hatching denotes the calculated area under the curves. The Global Temperature-change Potential over a given time horizon is equal to the value on the curve at that point in time relative to that of carbon dioxide. (Source: IPCC, 2013)

These figures show how Global Warming Potential (GWP) and Global Temperature-change Potential (GTP) emissions factors are calculated. As I will discuss in Chapter 2.3, radiative forcing over a 100-year time horizon (GWP_{100}) is the conventional basis of comparison for GHG inventory accounting. Therefore, Figure 2. 1 also highlights the importance of the choice of time horizon over which comparisons are made, and leaves open the question of how effectively these conventions communicate the climate impact of non-CO_2 GHGs.

2.2 The environmental impacts of ruminant agriculture

The wide-reaching environmental impacts of livestock production came to the forefront of climate policy in 2006 with the publication of the Food and Agriculture Organization (FAO) report, “Livestock’s Long Shadow” (Steinfeld et al. 2006). Crop and livestock production generates GHG emissions primarily in the form of CO_2, CH_4, and N_2O within the boundary of the farm itself, and upstream to produce certain inputs to the farm such as feed, fertilizers, and pesticides. Ruminant agriculture is also a significant driver of land use change (LUC), which causes GHG emissions as well. This section outlines the major sources of emissions associated with ruminant agriculture, mechanisms for mitigation, and impacts beyond GHGs. The relative impacts of these emissions sources are calculated in Chapter 4 for UK ruminant production systems. I also note that, while goats, sheep, llamas and alpacas are all ruminant livestock species, this thesis focuses exclusively on cattle systems.

2.2.1 Sources of production emissions and mitigation options

Ruminant agriculture causes GHG emissions directly through certain biological processes, and indirectly due to the use of inputs on the farm. Table I.11 in Appendix I defines each category of emissions, and notes whether it is included in the National Inventory Reporting (NIR) framework through the UNFCCC (see Chapter 2.4.1). The accounting of production emissions in this thesis adopts an 'operational control' approach, which includes all emissions categories over which a land manager has agency (see Chapter 3.2.1). For example, production emissions include the emissions associated with producing chemical fertilizers because a farmer decides how much fertilizer to buy, but do not include transport emissions because a farmer does not decide how the products are transported beyond the farm gate. This section describes the most important emissions sources and the various interventions available to mitigate them.

Enteric methane

Ruminants get their name from one of four compartments of their stomach, called a rumen, which can digest highly cellulosic feeds due to the presence of methanogenic bacteria. Ruminant digestion is responsible for around 30% of global methane emissions and, within the agriculture sector, 65% of methane emissions come from cattle farming (FAO 2022; Tseten et al. 2022).

There are several ways to reduce enteric methane emissions. Feeding cattle a diet higher in starches and lower in fiber alters the chemical reaction in the rumen, resulting in lower methane emissions (Kebreab et al. 2010). These diets are more easily digestible, which improves the feed conversion efficiency (FCE), meaning more product per input of feed, which also reduces methane emissions per kilogram of product (Capper et al. 2009; Herrero et al. 2013, 2016). It is also possible to selectively breed cattle that emit less methane as a result of natural variation in the abundance of methanogenic bacteria (Beauchemin et al. 2022; Y. de Haas et al. 2021).

Technological developments in feed additives have yielded promising yet controversial results. These additives, known as enteric methane inhibitors, have been derived from many substances including algae, tannins, and essential oils (Xie et al. 2025). One inhibitor derived from a species of seaweed, *Asparagopsis taxiformis*, is effective in reducing enteric methane, but contains bromoform, which is a probable carcinogen (Sofyan et al. 2022). Studies have shown that small amounts of bromoform residue may appear in milk, though these trace amounts are not likely to pose a risk to humans (Cressey et al. 2025). Nevertheless, perceived negative human and animal welfare effects of bromoform have limited the uptake of *A. taxiformis* (Glasson et al. 2022). Furthermore, feed additives are mainly applicable in housed systems as opposed to grazed, which limits the scalability of this intervention.

A synthetic inhibitor, 3-nitrooxypropanol (3-NOP), has also been studied with positive results in methane inhibition and with no negative effects on the animal (Kebreab et al. 2023). 3-NOP is currently approved in the European Union (EU) and UK. Despite meeting all necessary food safety requirements, the rise in the use of this additive has been met with misinformation in the media, suggesting a lack of public acceptance of the additive (Eardley et al. 2024).

Manure management

Cattle manure emits methane and nitrous oxide at rates dependent on the handling and storage methods used (FAO 2023). These emissions can be mitigated using different interventions at each stage of the manure management process. For housed operations, removing manure from the barn more frequently reduces emissions (Mohankumar Sajeev et al. 2018). Following removal from the barn, slurry acidification of liquid manure and anaerobic digestion of solid and liquid manure can further mitigate GHGs. However, anaerobic digestion typically requires additional organic substrate which can generate competition for biomass, reducing or even eliminating net climate benefits (Searchinger et al. 2021; Styles et al. 2022). Appropriately covering stored liquid slurry can also prevent volatilization of GHGs (Mukherji et al. 2023).

Synthetic inputs and applied nitrogen

Nitrogen is applied to cropland for cattle feed and pasture in different forms. Synthetic nitrogen fertilizers, organic fertilizers (manure), and crop residues are applied based on the nutrient requirements of the crop. Synthetic pesticides are usually imported from abroad and applied on the farm. The production of synthetic fertilizers and pesticides would not be captured in national reporting of agricultural emissions, but would appear in a Life-Cycle Assessment (LCA) or supply chain emissions accounting framework.

Once applied on the soil, crops take up some of the nitrogen, and the remainder can be lost through nitrate leaching, or emitted to the atmosphere as nitrous oxide during nitrification and denitrification processes. These emissions can be mitigated through more precise estimations of a crop's nitrogen use efficiency, improved timing and method of nutrient application, or biological nitrification inhibitors (P. Smith et al. 2007). The use of nitrogen-fixing crops such as legumes and clover can also reduce the need for fertilizers, though there may be a trade-off with crop yield (See Chapter 5). Nitrogen leaching into waterways also damages natural ecosystems and waterways surrounding farms (See Chapter 2.2.3).

Energy use

Cattle farms consume fuel for farm equipment such as tractors. They also use electricity for heat, lighting, and mechanized milking parlors. Improved energy efficiency and electrification of farm equipment alongside decarbonization of the grid are the primary opportunities to mitigate on-farm energy emissions (Searchinger et al. 2021).

Feed production

The emissions required to produce feed beyond the farm gates can be estimated using global or regional emissions factors from a database such as those included in Chapter 2.4.3. Improvements in the production emissions of imported feed would not appear in the farm-level emissions calculation unless the feed supplier recorded and communicated data down the supply chain. However, improved FCE reduces the quantity of feed required, thus reducing the associated production emissions. Altering the composition of the feed basket to lower-emissions feeds can also reduce the impact of feed production, so long as productivity is not compromised.

2.2.2 Land use change

LUC emissions are captured in a national inventory of countries actively experiencing deforestation. In corporate supply chains, LUC can be allocated using one of several methods discussed in Chapter 2.3. This section discusses the contribution of ruminant agriculture to LUC emissions and highlights opportunities to abate them.

Ruminant systems are land-intensive with approximately three-quarters of the world's agricultural land dedicated to pasture and cropland to support them (Ritchie and Roser 2019). Furthermore, cattle grazing and feed production was the largest agricultural driver of tree cover loss from 2001 to 2015 (Goldman and Weisse 2024). However, not all agricultural land is created equally. Some land is best for high-yielding production of crops suitable for human consumption, while other regions are best used as grazing land (Schneider et al. 2022; Blackwell et al. 2024). In most cases, the carbon sequestered by human-appropriated land use is less than what the land would sequester as an unmanaged ecosystem (Searchinger et al. 2018). This is especially true in the case of peatland where flooded, carbon-rich soil is drained and used as extremely fertile agricultural land. When peatland is drained, CO_2 and N_2O are emitted in large quantities. Wetted peatland, however, emits methane due to the anaerobic conditions. Many national agricultural mitigation strategies involve vast rewetting of peatlands, particularly across Europe, which could displace the food produced on that land (CCC 2025; Kopsieker et al. 2021).

2.2.3 Other outcomes

Although this thesis focuses on the impacts of ruminant agriculture on climate change, there are many other environmental and ethical outcomes considered in the livestock management literature. This section highlights the significance of these outcomes and discusses how they fit into an LCA framework.

Biodiversity and soils

Land use change for agriculture is the largest driver of biodiversity loss, responsible for at least 80% of all LUC globally (Campbell et al. 2017). At the farm level, dependence of the modern food system on pesticides and other synthetic inputs further drives biodiversity loss (Benton et al. 2021). In recognition of the dependence of humanity on thriving and functional ecosystems, the literature explores alternative methods of farming that enable both food production and biodiversity to coexist (McLaughlin and Mineau 1995; Cozim-Melges et al. 2024).

Conservation agriculture refers to farming methods that preserve soil structure and protect biodiversity (Hobbs et al. 2008; Palm et al. 2014). More recently, some of these practices have been described as regenerative agriculture with an additional focus on the sequestration and storage of soil carbon (Rhodes 2017; Schreefel et al. 2020). However, there is no unified or formal definition for regenerative agriculture, which has led to confusion regarding which practices and outcomes it does and does not include (Newton et al. 2020; Cusworth and Garnett 2023). Furthermore, analysis of a wide range of regenerative interventions shows variable effects for biodiversity, and mostly negative impacts on yield (P. Burgess et al. 2019). The tension between efficient agricultural production and improved on-farm biodiversity is best framed by the concepts of *land sparing and land sharing*, which is discussed in Chapter 2.3.6.

There are many different indicators that can be used to assess the impact of farming on biodiversity. Thus, the incorporation of biodiversity into LCA methodology is a point of contention in the literature (Crenna et al. 2020; Damiani et al. 2023). In recent years, companies have begun to report their impact on biodiversity, and standardizing bodies have developed methodologies to buy and sell biodiversity offsets and credits (Maron et al. 2025; Wunder et al. 2025). However, given a lack of consensus around how best to quantify biodiversity impacts, there are open questions around which metrics are most appropriate in these cases (Bromwich et al. 2025).

Water quality and water use

Nutrient runoff from cropland due to over-application of fertilizers and poor manure management significantly affects the function of aquatic ecosystems by increasing the risk of eutrophication and dead zones (Dwyer et al. 2024). The damage to nature caused by nutrient pollution has been the focus of public policy in certain countries such as the Netherlands (see Chapter 6), whose government has placed strict limits on fertilizer use. Within the LCA literature, pollution from nitrogen and phosphorous fertilizers is typically quantified based on the eutrophication potential (Morelli et al. 2018).

Ruminant agriculture also utilizes vast quantities of freshwater both to support the animals themselves as well as to grow their feed crops. It is estimated that approximately 40% of annual agricultural water use is for livestock production, with studies finding that ruminants are water-inefficient among livestock types (Wisser et al. 2024; Heinke et al. 2020). In LCA, water use is often reported as liters of water per kilogram of product (Legesse et al. 2017). LCA literature also includes the use of a water footprint weighted based on regional water scarcity to incentivize the production of water-intensive products in water-abundant areas (Ridoutt and Pfister 2010).

Animal welfare

Concerns over the wellbeing of livestock animals has driven an interdisciplinary field of research since the advent of intensive farming operations (Fraser et al. 2013). Animal welfare cuts across multiple fields including animal behavior, epidemiology, and nutrition with the aim to improve the quality of life for kept livestock. It is arguably a subjective concept, where ethical judgments and beliefs regarding the value of an animal's life can influence an individual's definition of welfare (Mason and Mendl 1993; Browning 2022). To better understand the many facets of animal welfare, a range of mechanisms to quantify and qualify it have emerged.

Early framings of animal welfare are based on qualitative characteristics such as 'the Five Freedoms,' which state that animals should be free from pain, hunger, discomfort, fear, and should be able to move normally (Farm Animal Welfare Council 2009). In corporate supply chains, dozens of welfare-based certifications and labels have been developed that typically relate to how frequently animals are kept outside, whether antibiotics or hormones are used, and the level of confinement (Main et al. 2014; Waite et al. 2024).

Recently, efforts have been made to develop frameworks that quantitatively incorporate animal welfare into LCA. Indicators include the number of years of animal suffering, the number of lives lost, and the number of days spent outside, with studies proposing methods to weight and combine these indicators into a single score (Bartlett et al. 2023; Scherer et al. 2018). Other indicators involve more physiological data such as heart rate or adrenal activity as measures for stress (Broom 2011). However, standardized incorporation of animal welfare into LCA remains an under-studied area of research (Lanzoni et al. 2023).

2.2.4 Land use policy in Europe

Chapters 4 and 5 of this thesis pertain to agricultural mitigation pathways in the UK, and Chapter 6 explores land use strategies in both the UK and EU. This section therefore summarizes climate strategies for the land sector in these jurisdictions.

United Kingdom

Though the context of this thesis pertains to the UK as a whole, it should be noted that the Devolved Administrations of Scotland, Wales, and Northern Ireland have their own policies for farm subsidy schemes and agricultural transition plans. They also differ in their approaches to legislating carbon budget implementation.

In 2016, the UK voted to leave the EU, which came into effect in 2020. No longer eligible for EU farm subsidies, the UK developed a replacement scheme. In 2018, the Department for Environment, Food & Rural Affairs (DEFRA) announced in its 25-year plan the intention to prioritize better land management for a "Green Brexit" (DEFRA 2018). The plan also announced the new Environmental Land Management schemes (ELMs) promising 'public money for public goods,' with a focus on nature recovery, afforestation, and converting to farming practices often described in academic literature as 'agroecological' (DEFRA 2023b). Note that while this thesis uses the term 'afforestation' to refer to tree-planting, this terminology is not explicitly used by DEFRA with regard to ELMs. Rather, the ELMs guidance refers to tree-planting as 'woodland creation.' In reference to the prior comment regarding the Devolved Administrations, ELMs pertain solely to England.

ELMs represents a unique co-designed policy facilitated by DEFRA that engages agri-environment stakeholders to develop an implementable strategy (Little et al. 2024). There are important questions, however, around who constitutes the 'public,' and what is meant by 'goods' (Coulson and Milbourne 2022). ELMs represents a shift from 'productivist' ideals, which formed the foundation of EU subsidies following World War II and prioritized food production as the primary good, to redefining 'goods' to value other attributes such as resilience, carbon storage, and biodiversity (Burton 2004; Cusworth and Dodsworth 2021).

Alongside these national policies, the governmental advisory body called the Climate Change Committee (CCC) releases national carbon budgets that outline net zero pathways by sector. The pathway for the agriculture sector in the most recent Seventh Carbon Budget involves modest reductions in production emissions through technological interventions, substantial peatland restoration, and afforestation of approximately 20-30% of the UK's grazing land (CCC 2025). The CCC's model assumes that trade flows remain constant and meat consumption decreases. In other words, the model assumes that the UK would not import more ruminant products to make up for lost production, nor that remaining farmland would intensify production. While ELMs explicitly incentivizes repurposing land for carbon storage, concurrent policies to address consumption of animal products are lacking. Thus, this mitigation pathway risks increasing the UK's contribution to global land use competition if diets do not change.

Importantly, the net zero pathway in the CCC's Seventh Carbon Budget does not show the agriculture sector achieving net zero on its own (CCC 2025). Rather, emissions for agriculture and aviation—two hard-to-abate sectors—are reduced by between 30-50%, and biogenic and geologic removals counteract remaining national emissions. It is important to distinguish that this framing of net zero (see Chapter 2.3.3) is an objective for the national economy rather than for each individual sector when discussing mitigation obligations. Chapter 6 builds on this concept to disentangle the implications of net zero as a national (or global) objective, particularly in terms of what it means for corporate stakeholders whose operations may span many countries.

Non-governmental organizations have also published reports outlining possible strategies for the UK land sector. The 2024 Net Zero Transition Plan for the UK food system aligns with the CCC's supply-side interventions, but more explicitly outlines the need for demand-side interventions such as shifting diets and reduced food loss and waste (WRAP and IGD 2024). The

Agri-Food Network's Roadmap to 2050 similarly projects scenarios in which between 1 and 5 million hectares of agricultural land are set aside for forestry, peatland restoration, and bioenergy crops enabled mainly by shifting diets (Agri-Food for Net Zero Network 2025). The National Food Strategy takes an approach focused on human health and a just transition, and also suggests the need for a substantial decline in the consumption of ruminant products (National Food Strategy 2021). Given that very few cattle farms in the UK are profitable without government subsidies (Collas and Benton 2023a), ELMs payments could have a significant impact on the number of farms that continue to produce food.

While policymakers and researchers have proposed what land management priorities ought to be in the UK, it is ultimately the farmers and land managers whose decisions will determine the future of the land sector (Thompson et al. 2026). According to DEFRA's most recent Farm Practice Survey, the main actions farmers are taking to reduce their emissions are shifting to renewable energy and recycling (DEFRA 2025a). Based on my calculations in Chapter 4, on-farm energy use is the smallest source of emissions in UK beef and dairy production (using GWP_{100}), suggesting that this focus on renewable energy is only a small part of a much broader transformation needed. Farmers who do not take measures to reduce their emissions cite a lack of clear guidance, a lack of financial incentive, and a perception that their farms already have a minimal impact on the climate. These gaps must be bridged to ensure policy goals translate into action, as I discuss at greater depth in Chapter 6.

European Union

The EU introduced the Common Agricultural Policy (CAP) in 1962 to support rural economies and ensure the security and affordability of the region's food supply (European Commission 2025a). In 2021, a CAP reform was adopted, which aimed to align farm subsidies with the

European Green Deal and the Sustainable Development Goals, and improve the livelihoods of smaller farmers (European Commission 2021; Pe'er et al. 2019).

As with ELMs, the new CAP places emphasis on carbon sequestration and storage, peatland restoration, soil health, and bioenergy (European Commission 2025c; Nordbeck et al. 2025). CAP also includes payments for improved efficiency and technological interventions such as enteric methane inhibitors and improved manure management. Furthermore, the European Commission launched the Carbon Removals and Carbon Farming regulation in 2024, which offers a regional framework for verifying and incentivizing land-based removals (European Commission 2024). As with the shift to agro-ecological practices under ELMs in the UK, the upscaling of practices in the EU that enhance land-based removals also presents a trade-off between food production and carbon storage.

2.3 Greenhouse gas and land use metrics

Greenhouse gas metrics are simple models that serve the purpose of comparing a chosen impact of one gas to that of another over a given time horizon. Since the Kyoto Protocol in 1997, GHG accounting has largely been based on the relative integrated radiative forcing of a pulse of non-CO_2 gas to that of CO_2 over 100 years (UNFCCC 1997). However, Article 4 of the 2015 Paris Agreement requires a 'balance of anthropogenic emissions by sources and removals by sinks' (UNFCCC 2015). Given how methane, a short-lived GHG relevant in ruminant systems, behaves differently to cumulative GHGs in the atmosphere, there is contention as to whether the target in the Paris Agreement necessitates consideration of methane's distinct nature. Considering nearly 70% of the world's methane emissions come from agriculture, this physical property is most pertinent (P. Smith et al. 2021).

In addition to emissions from agricultural production, a significant amount of terrestrial carbon has been lost to the atmosphere due to changes in land use from native vegetation cover to agricultural uses (Haberl et al. 2007). Recent LUC emissions are typically accounted for in corporate Scope 3 reports (WRI and WBCSD 2022a) or in national inventories for countries experiencing ongoing LUC (FAO 2020; IPCC 2003). There are several different methods of measuring LUC, which vary in their assumptions about temporal and spatial boundaries.

This section therefore discusses conventional and novel GHG and land use metrics, and offers some more philosophical thoughts regarding the nature and implications of how these metrics are used.

2.3.1 Global Warming Potentials

The advent of the IPCC and national GHG emissions reporting in 1990 necessitated a mechanism by which emissions of different gases could be compared and ultimately traded with one another (IPCC 1990). The GWP was initially introduced, however, in the 1989 Scientific Assessment of Ozone Depletion following the Montreal Protocol to convey the severe effects of ozone-depleting substances (IPCC et al. 2005). It later became convention to report GHGs based on GWP, and the Kyoto Protocol formalized the use of GWP over a 100-year time horizon (GWP_{100}) in 1997 (UNFCCC 1997).

GWP_{100}, reported as carbon-dioxide equivalents (CO_2e), is calculated as the integrated radiative forcing resulting from a pulse of a non-CO_2 gas relative to that of CO_2 over a chosen time horizon, or the relative areas under the curves shown in Figure 2. 1(a) (Lashof and Ahuja 1990). The IPCC also reports GWP emissions factors over 20- and 500-year time horizons. The justification for the conventional use of the 100-year time horizon is debated (Rodhe 1990; Myhre et al. 2013), with some arguing it became convention simply for being the middle of the three values (Keith P. Shine 2009). Alternatively, a 100-year time horizon is implicitly aligned with the 3.3% discount rate used in economic decision-making, giving GWP_{100} relevance in policymaking (Sarofim and Giordano 2018). This approach, however, implies that carbon mitigation should be optimized in the same way economics optimizes money, which some argue is inappropriate because not all environmental damages can be appropriately represented by money (Fearnside 2002a)

GWP is considered a 'stock' metric due to its focus on the impact of a fixed quantity of a gas emitted over a short period, as opposed to 'flow' metrics, which focus on the impact of a sustained change in emissions rates, which I will discuss in the next section. Other stock metrics have been proposed, though they are less commonly used. For example, the Global Temperature-change Potential (GTP) calculates the change in temperature at a fixed point in the future (e.g. after 100 years) caused by a pulse emission of a gas, relative to that of CO_2. Both GWP and GTP can also be defined for a sustained emission, in which case they become flow metrics (Keith P. Shine et al. 2005), although they are almost never used in this way. GTP was proposed on the grounds that temperature is a more appropriate indicator of climate damages than radiative forcing, which some argue is beneficial for short time horizons (S. J. Smith and Wigley 2000). However, GTP is more sensitive than GWP to the choice of time-horizon and to the non-linear impact of uncertainty in future climate change (K. P Shine et al. 2007).

Though GTP indices are sometimes reported alongside GWP, the latter continues to serve as the default metric for national and corporate emissions reporting due to its simplicity of use and its ability to incorporate new GHGs or update values for existing gases (Jan S. Fuglestvedt et al. 2003). Nevertheless, it has faced criticism in the literature (Keith P. Shine 2009). Specifically, scientists have argued that the comparison of radiative forcing over 100 years distorts and undervalues the near-term benefits of reducing short-lived GHGs (S. J. Smith and Wigley 2000; Allen et al. 2016). Methane, for example, has a half-life of approximately 12 years. Whilst in the atmosphere, it acts as a powerful greenhouse gas. Thus, measuring its impact over 100 years dilutes the strong radiative forcing in the first two decades while also implicitly extending the harm caused by the short-lived pollutants over periods much longer than their lifetimes.

In contrast with stock metrics calculated over 100 years, indices for short-lived GHGs calculated using GWP or GTP over 20 years are much higher. GWP_{100}, for example, yields a value of 27 for biogenic sources of methane while GWP_{20} is 80 (IPCC 2021c). For the development of climate policy, this distinction means that a tonne of methane abatement could be worth 27 or 80 tonnes of CO_2, depending on the chosen time horizon. Recognizing the potential implications for GHG mitigation, some have advocated for entities to report GWP over multiple time horizons (Ocko et al. 2017). However, consideration of GWP over a shorter time horizon could place more emphasis on methane mitigation at the expense of CO_2 reductions. Because temperature change is directly correlated with the cumulative emissions of CO_2 in the atmosphere (Allen et al. 2009), these trade-offs must be carefully navigated as mitigation policies aligned with the Paris Agreement are developed.

It is also important to consider the distinction between the choice of metric (GWP or GTP) and the choice of the time horizon. These two discrete choices determine what information is conveyed by the indicator. For example, GWP_{100} for methane is approximately equal to GTP over a 40-year time horizon. Therefore, GWP_{100} conveys the relative impact on temperature in 40 years' time. This nuance is often lost, which affects the usefulness of these values in setting targets related to limiting peak warming.

2.3.2 GWP and short-lived pollutants*

In response to the shortcomings of stock metrics and their limitations when accounting for the short-lived properties of GHGs such as methane, Allen et al. (2016) and others proposed a 'flow-based' metric in 2016 known as GWP-star (GWP*) (Allen et al. 2016, 2018; Cain et al. 2019; M. A. Smith et al. 2021). This method of emissions accounting looks at the rate-of-change, or 'flow,' of short-lived GHGs over a 20-year window looking either back in time at historical emissions, or forwards in time to understand the impact of a decision on the future climate (Equation 1).

$$E^*{}_t = 128 \times E_{CH_4}(t) - 120 \times E_{CH_4}(t-20) \qquad (1)$$

E_x represents emissions of gas x
t represents the year of reporting
E represents emissions in time t in CO_2-warming equivalents*

Calculating cumulative emissions under GWP* more closely mirrors the effect of GHGs on temperature compared to cumulative GWP_{100} emissions (Lynch et al. 2020). Thus, emissions calculated using GWP* are reported as CO_2-warming equivalent (CO_2-we). The choice of the 20-year window was largely a convenient one as it yielded a good fit with other climate models, though this decision is not nearly as consequential as the choice of time horizon for GWP discussed in the previous section. One could equally calculate GWP* over any time horizon with different coefficients and achieve roughly the same result.

The difference in atmospheric behavior between methane and CO_2 is shown in Figure 2. 2. Emissions of both gases are sustained for 50 years, then decline to zero. For methane, the radiative forcing reduces to nearly zero approximately 20 years after emissions reach zero. For CO_2, however, radiative forcing persists for centuries. The authors argue that a metric more closely aligned with the temperature impacts of GHGs is useful for setting climate targets that effectively limit contribution to further warming (Cain et al. 2019).

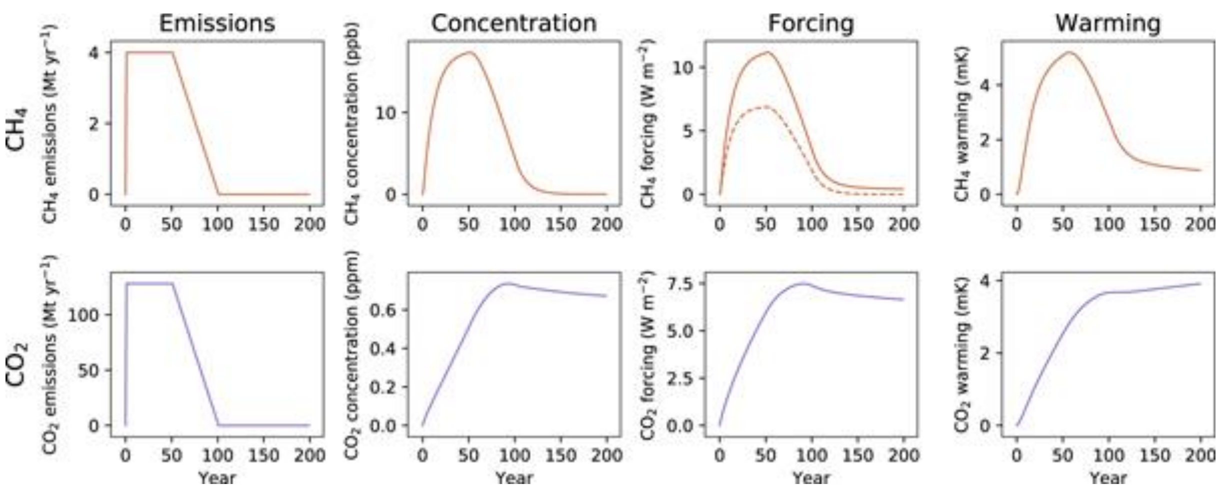

Figure 2. 2 Effects of sustained emissions for 50 years, followed by a decline to zero over the next 50 years, of methane (orange, top) and CO_2 (blue, bottom) on atmospheric concentration, radiative forcing, and temperature. (Source: Lynch et al. 2020)

Others have shown that, even with rapid mitigation of fossil-based emissions, ambitious reductions of agricultural methane are necessary to avoid 2°C of warming above pre-industrial levels, or reduce to the level of peak warming (Clark et al. 2020; Reisinger 2024; Duffy et al. 2025). Furthermore, distinguishing between stocks and flows in the agriculture sector is crucial to the development of effective climate policy (Lynch et al. 2021). Thus, the debate around how to address short-lived GHGs is highly relevant to ongoing conversations regarding climate mitigation in the agriculture sector.

As with GWP_{100}, GWP* has also faced criticism. The critiques of GWP* are best understood in the context of its advocates. Ruminant agriculture is one of a few sectors with an emissions profile dominated by methane. Thus, researchers have explored whether methane should be considered separately to CO_2 with the aim to achieve 'no further warming' (McAuliffe et al.

2023; Wheatley 2024; Lynch and Garnett 2021). In response, corporate stakeholders in New Zealand, where ruminant methane accounts for half of the national emissions under GWP_{100}, have lobbied for separate methane targets informed by GWP* that would significantly reduce the level of mitigation needed to meet a target of 'no further warming' compared to a target of 'net zero' using GWP_{100} (Barth et al. 2023; DairyNZ 2023). In California, others have applied the GWP* concept to develop 'climate neutrality' pathways for beef and dairy, often with a basis in the economic or biodiversity benefits of ruminant grazing (Place et al. 2022; Mitloehner et al. 2020; Rocha 2022; McCabe et al. 2023). However, New Zealand and California could equally set targets to achieve 'net cooling.' In other words, it is not the metric that leads to reduced mitigation ambition, but rather the motivations of the entity applying it when setting a target.

Cusworth et al. (2023)'s piece entitled "When you wish upon a (GWP) star" introduces the concept of *reflexive performativity* in the field of metrology. The authors argue that metrics are inherently performative, meaning that choices around how an impact is measured effectively predetermine how that impact is then managed. They claim that GWP*'s mathematical effect of minimizing the perceived impact of stable or gently declining methane emissions has been abused by actors within the livestock sector to reduce their mitigation responsibility. This is indeed a problem, but not an insurmountable one, as I will discuss in Chapter 2.3.7 and explore through stakeholder interviews in Chapter 6.

In summary, there is a trend wherein GWP* is used to justify reduced levels of methane mitigation. Criticisms from researchers have centered on this perceived reduction in responsibility for the sector to contribute to climate mitigation. Referring to Equation 1, if a country maintains an annual reduction of methane of 0.3% per year for over 20 years, national warming-equivalent emissions from methane would be zero relative to a recent base year. Many have argued that this characteristic of the GWP* formula benefits nations whose methane emissions increased long ago by ‘grandfathering in’ historical methane emissions (Garnett et al. 2017; Carter and Urbancic 2023; Rogelj and Schleussner 2019). Considering a counterfactual further into the past shows that even stable concentrations of methane hold the global temperature higher than it would have been in the absence of those emissions, which one article dubs the ‘marginal warming’ effect (Reisinger et al. 2021). In response to New Zealand’s split-gas target, environmental non-profits and activists fiercely opposed the ‘no further warming’ target in an open letter to the Prime Minister citing issues of fairness and lack of mitigation ambition (Shindell et al. 2025).

This concept is important when defining what constitutes a mitigation strategy that is aligned with the Paris Agreement to avoid 1.5 or 2 degrees of warming (Reisinger 2024; Schleussner et al. 2019). It has therefore been pointed out that, with a target of ‘no further warming,’ global temperatures could hypothetically stabilize above 2 degrees, concluding that temperature neutrality alone is not a sufficient condition to meet the goals of the Paris Agreement (Duffy et al. 2025; Tanaka and O’Neill 2018).

Others have suggested that GWP* does not meet the criteria for an attributional metric but should instead be seen as a simple climate model whose utility is limited to assessing global temperature trajectories (Meinshausen and Nicholls 2022). Meinshausen and Nicholls (2022) argue that emissions metrics should not be dependent on what has occurred in the past, and the sign of a GHG metric should never be negative, as is the case with GWP* when the rate of methane emissions is declining, to avoid perverse incentives in cases where a metric functions as a way to trade quantities of different GHGs.

The issue of grandfathered emissions in relation to meeting the Paris Agreement goals sparked an interesting exchange between critics and the authors of GWP*. Critics argued that GWP* at the sub-global scale "introduces a preferential treatment of countries…that have large historical methane emissions" (Rogelj and Schleussner 2019). Rogelj and Schleussner (2019) claim that the reliance of GWP* on arbitrary decisions such as a base year are problematic and not consistent with national emissions accounting conventions. The authors of GWP* rebut that the value of GWP_{100} for methane is frequently updated based on the latest science and, considering the use of GWP_{100} is not explicitly required by the Paris Agreement, accounting methods should themselves be updated according to the latest science (Cain et al. 2021). In response to the grandfathering argument, Cain et al. (2021) explain that GWP* can in fact facilitate the equitable distribution of responsibility based on historical warming as opposed to emissions. Additionally, they point out that whether entities should have to undo historical warming for either methane or CO_2 is a political decision more easily made with GWP*. Rogelj and Schleussner respond by agreeing that GWP* is not inherently unfair, but rather that unfairness comes from the use of the metric (Rogelj and Schleussner 2021). Ultimately, both sides seem to recognize the significance of implicit choices embedded within a metric and how those choices might influence climate policy.

My master's thesis investigated the implications of using GWP* in national target setting through expert interviews with policymakers. I found, in addition to evidence aligning with the critiques discussed in this section, that the calculation itself represents a substantial obstacle to applying GWP* in the national context (Zionts 2018). Not all companies or countries have the 20 years of historical emissions data required to calculate GWP* for an attributional inventory, though it would be possible to calculate the impact of decisions on future temperatures relative to a present baseline as I explore in Chapter 4. Furthermore, stakeholders claimed that GWP*'s additional step of calculating a rate-of-change makes it not only more difficult to calculate, but also more difficult to communicate to the public (Zionts 2018).

Despite the critiques, there is consensus that long- and short-lived GHGs should be reported separately and considered with separate targets (Allen, Peters, et al. 2022), echoing similar calls from scientists over two decades earlier (J.S. Fuglestvedt 2000). Though the objective to mitigate climate change while meeting the material needs of a growing population appears to be shared across the literature, tensions surrounding methane reduction requirements have grown, creating a gap for this thesis to disentangle mitigation responsibilities from vested interests. From the literature, critics of GWP* have demonstrated the issues with applying a flow-based metric to an annual inventory. I largely agree with these critics, though I also argue that there is space for warming-based metrics as forward-looking tools that can be used to understand the temperature effects of decisions made today. Thus, Chapter 4 explores the ways in which GHG metric choice truly influences mitigation priorities for ruminant agriculture.

2.3.3 Net zero

Corporate and national climate targets are described by terms such as 'carbon neutrality,' 'climate neutrality,' or 'net zero.' All three terms relate to the balance of anthropogenic sources of GHGs with sinks as required by the Paris Agreement, though they differ in which GHGs and Scopes are included in the target, and in the level of accepted use of removals (Rogelj et al. 2021). Carbon neutrality refers to a state in which carbon dioxide emissions are no longer contributing to global temperature changes (net zero CO_2 emissions), whereas climate neutrality includes all anthropogenic GHGs (net zero GHG emissions) (Allen, Friedlingstein, et al. 2022). Both carbon and climate neutrality targets do not necessarily include decarbonization of the entire supply chain. Furthermore, true net zero requires substantial reductions across all Scopes (See Chapter 2.4.2) and sectors *before* removals can be used, whereas climate and carbon neutrality do not restrict the use of removals to residual emissions (Axelsson et al. 2024).

The 'net' in net zero refers to negative emissions (or removals) that counterbalance any residual or 'hard-to-abate' emissions. Removals can either be geologic, such as through DACCS, or biogenic, such as through plant growth or soil carbon sequestration. At present, most deployable removals are biogenic, and would require vast areas of land at scale (S. Smith et al. 2024). Overreliance on land-based removals risks driving land use change due to competition with food production (Westaway et al. 2023). While removals are relevant in national emissions accounting, or corporate accounting within the supply chain, offsets refer to removals purchased outside of a company's supply chain. The validity of biogenic offsets has been questioned on the basis of their permanence and additionality (Greenfield 2023). Some have also argued that biogenic offsetting risks double counting—if a country plants trees and sells carbon credits to a company, the removal would appear both in the national emissions report and the corporate account of the credit buyer (Rogelj et al. 2021).

The stock-versus-flow binary discussed in Chapter 2.3.2 is also relevant in defining net zero. The wording of the Paris Agreement is not clear about what a "balance of sources and sinks" means in the context of short-lived GHGs (J. Fuglestvedt et al. 2018). Achieving net zero GHGs aggregated using GWP_{100} may fail to halt further warming because temperature change is proportional to concentrations of long-lived GHGs, and to the rate of change of short-lived GHGs (IPCC 2018). Therefore, some have argued that net zero targets should be based on radiative forcing or warming rather than aggregated CO_2-equivalent emissions compared over an arbitrary time horizon (Jenkins et al. 2018; Allen et al. 2018). Regardless of the basis of comparison, there is agreement that disaggregated emissions should be reported to allow for the application of different measurements (Allen, Peters, et al. 2022).

In the case of ruminants, methane's short-lived nature has raised questions around how the sector fits within a net zero target, especially if net zero is defined by the effect of GHGs on temperature. Some have argued that, if the goal of net zero is to stabilize temperatures, ruminant methane emissions must only decline by 0.3% per year according to the equation in Chapter 2.3.2 (Lynch and Pierrehumbert 2024). Methane mitigation can be achieved without reducing cattle populations through improvements in efficiency or technological interventions (See Chapter 2.2.1). However, this framing overlooks crucial impacts of ruminant agriculture beyond warming such as competition for land use and loss of biodiversity (See Chapter 2.2.3).

The net zero concept has been a focus of climate target setting in the past decade, although questions remain around how sub-global entities should contribute to a global state in which further warming is minimized (Hale et al. 2024). According to the Net Zero Tracker, hundreds of companies and governments have net zero targets, though very few meet important criteria such as appropriate governance, coverage, and minimal use of offsets (Hale et al. 2022; Lang et al. 2023). Various approaches to corporate and national target setting are discussed further in Chapter 2.4. This gap between climate targets and actualized mitigation is a significant obstacle to meeting the goals of the Paris Agreement that I explore at length through stakeholder interviews in Chapter 6 (Fankhauser 2021; Schumer et al. 2025).

2.3.4 Direct and statistical land use change

In addition to setting targets around GHGs, many corporate and national entities set targets to minimize their contribution to LUC and deforestation for "high deforestation risk" commodities such as soy, cocoa, and beef (Curtis et al. 2018). As with GHGs, there are several ways to calculate and report LUC emissions. Countries report terrestrial carbon emitted (or sequestered) in their NIR as part of the UNFCCC process (IPCC 2003). However, the allocation of these emissions (or removals) along a corporate supply chain or product LCA is a topic of discussion in both academic and grey literature. Direct and statistical land use change (dLUC and sLUC, respectively), are common metrics used in corporate reporting. They are relevant in the achievement of corporate zero-deforestation commitments, and higher-level objectives such as the EU Deforestation Regulation (EUDR). dLUC and sLUC are grouped together here due to their similar biophysical calculations, which are distinct from those of indirect LUC discussed at the end of this section.

The IPCC defines LUC as the conversion of land from one cover type to another, such as from forest to agriculture (IPCC 2019). dLUC is one method for allocating the resulting carbon stock changes to commodities produced on recently deforested land. dLUC is calculated as the carbon stock change per unit mass of a commodity on recently changed land. This carbon stock change is annualized over 20 years into the past and allocated either equally or using linear discounting as illustrated in Figure 2. 3 (WRI and WBCSD 2022a). The metric is most relevant if a company can trace a commodity to a specific piece of land and has information about its LUC history. The 20-year annualization period was initially proposed in the IPCC's 1996 Guidelines for National GHG Inventories as an approximation of the time it takes for carbon stocks to stabilize following a deforestation event (IPCC 1996), though it is criticized as being highly subjective and having a significant impact on results (Maciel et al. 2022).

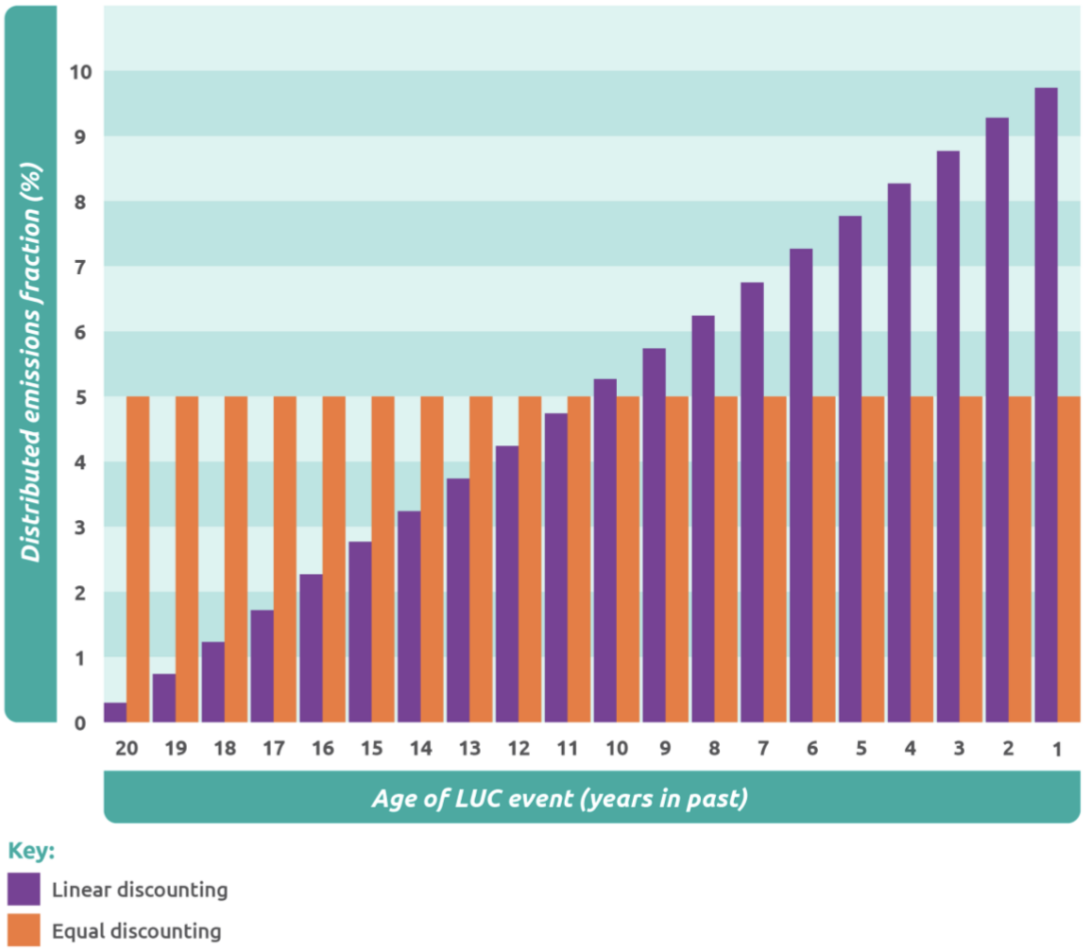

Figure 2. 3 Illustration of two methods for allocating historical dLUC emissions over 20 years. Linear discounting (purple) allocates a greater proportion of the emissions to more recently deforested land, whereas equal discounting (orange) annualizes emissions over the 20-year period. Source: (WRI and WBCSD 2022a)

As with the choice of time horizon used for GWP, this conventionalized 20-year window is another example of a discrete choice with significant consequences. dLUC effectively treats deforestation between 20 years ago and the present as a pulse emission, discounted over 20 years. In effect, this mechanism ignores any carbon loss that occurred more than 20 years ago and has major implications for how the metric is used. For example, if no deforestation has occurred on a piece of land in the past 20 years, but significant deforestation occurred 21 years ago, that carbon loss would not be captured using dLUC.

In practice, the near-term discounting period means that a company could achieve zero LUC emissions if they simply source from land that was cleared more than 20 years ago while other companies without LUC targets continue to buy products from the recently cleared land, highlighting the arbitrariness of the temporal boundary (Yarlagadda et al. 2025). Thus, there is skepticism as to whether dLUC-based zero-deforestation commitments can meaningfully contribute to the global reduction of LUC emissions (Addoah et al. 2025; Villoria et al. 2022). Furthermore, lack of supply-chain traceability remains a significant obstacle in reporting spatially explicit dLUC emissions, which is explored further in Chapter 2.4.2.

sLUC was developed to overcome limitations associated with dLUC, namely the need for high spatial resolution and supply chain traceability. This alternative method of LUC allocation calculates emissions at the country-level, rather than at the farm-level (Ponsioen and Blonk 2012). sLUC is calculated by measuring LUC emissions at the national level and allocating the resulting emissions based on one of two methods. The 'shared responsibility' approach allocates national LUC emissions equally to all products from the jurisdiction (Nemecek et al. 2019). The 'product expansion' approach only attributes LUC emissions to products whose land area expanded (Nemecek et al. 2019). The calculations in Chapter 4 utilize the former approach, applying data used in a prominent agricultural LCA meta-analysis (Poore and Nemecek 2018).

While this landscape-level approach may reduce the data requirements and better reflect the level at which land use governance decisions are made (Addoah et al. 2025), the perverse incentives seen with dLUC persist. Rather than influencing the farms from which companies source products, country-level sLUC would allow a company to eliminate LUC emissions from their supply chain by sourcing from countries without recent land use change. Evidence therefore suggests that, in the absence of strong governance, country-level zero deforestation commitments have limited ability to reduce LUC so long as a market for deforestation-linked products exists elsewhere (Alix-Garcia and Gibbs 2017; Garrett et al. 2019; Lambin et al. 2018).

dLUC and sLUC approximate the amount of recent deforestation linked to a corporate supply chain, which may be a useful piece of information to some. However, the fact that land use emissions using these metrics can be eliminated by shifting sourcing regions, rather than improving production, limits its usefulness in reducing global land use competition.

There is a third LUC accounting method, indirect LUC (iLUC), which is most relevant in understanding the impact of diverting foods such as corn to biofuel. Rather than measuring the LUC within a known system boundary as with dLUC and sLUC, iLUC uses econometric modeling to estimate LUC elsewhere due to decisions within the system boundary (Wicke et al. 2012). Although biofuels are beyond the scope of this thesis, this brief consideration of econometric iLUC is included to demonstrate understanding of the evolution of land use accounting more broadly.

The discourse surrounding all three LUC metrics relates primarily to how competition for finite land resources can be minimized. Thus, some companies claim to use "low iLUC risk" feedstocks such as waste and residue streams, though there is uncertainty regarding the available quantities of such feedstocks that do not have pre-existing uses (Plevin et al. 2010; O'Malley et al. 2021). Furthermore, it has been suggested that programmed parameters within iLUC models find GHG benefits for biofuels by assuming that higher demand for feedstocks will increase the price of food, resulting in reduced consumption to avoid leakage (Searchinger et al. 2015). The shortcomings of these approaches to calculating LUC emissions create the need for a more transparent LUC accounting mechanism that can effectively incentivize interventions that limit global land use competition.

2.3.5 Considering foregone sequestration and the carbon opportunity cost

The concept of foregone sequestration began with the consideration of "land occupation," which recognizes that human-appropriated land use has ecological and climate consequences. It is sometimes included in LCA as a proxy for impact on biodiversity, or used as an input to more complex biodiversity metrics (Doka et al. 2002; Müller-Wenk and Brandão 2010; Koellner et al. 2013; Waite et al. 2024). Some think of land occupation as a "prevention of regeneration," implying a carbon accounting counterfactual in which no human activity occurs (Doka et al. 2002). Furthermore, some have argued that the "missed potential carbon sink" should be included in LCA, supporting the conceptual usefulness of a no-human-activity counterfactual (Schmidinger and Stehfest 2012). These considerations acknowledge that, if land were not being used to meet the material needs of humanity, it would store large amounts of carbon (Milà i Canals et al. 2007; Chiarucci et al. 2010; Erb et al. 2018).

The Carbon Opportunity Cost (COC) is an indicator developed in response to this need for an LCA-compatible accounting mechanism that acknowledges foregone sequestration while also addressing the leakage incentivized by other LUC metrics that only consider the effects of recent deforestation (Searchinger et al. 2018). Searchinger et al. (2018) argue that COC incentivizes more efficient use of the world's finite land resources in a way that circumvents the need for opaque econometric models.

There are two methods to calculate COC, though they both give approximately the same result. The calculation of COC emissions factors using the 'looking back' method is based on the time-discounted, annualized average difference between historical native carbon stocks and global average yield across all land where that product is grown within a specified spatial boundary (Searchinger et al. 2018). Alternatively, the 'looking forward' method compares yields with the amount of carbon the land could store if it were allowed to naturally regenerate into the future. In both cases, the most inefficient use of land would be one where the crop yield is very low and the potential Net Primary Productivity (NPP) is very high. Figure 2. 4 communicates this concept with hypothetical countries each producing a crop. The color of each square represents the NPP, and the number represents the average yield per hectare. In this illustrative scenario, oats would have a low COC because the potential NPP in the oat-producing countries is low, while the crop yields are relatively high. The soy example in this illustration mirrors the reality of global soy production. Some soy is grown in the tropics where the potential NPP is high, while some is grown in more temperate places such as the United States. Most soy, however, is very high yielding. The COC makes the argument that there is no "good" or "bad" source of soy, but rather deforestation linked to soy production continues because the global demand for soy continues. Thus, the COC calculation allocates "blame" for the soy-linked depletion of native carbon stocks equally across all soy production in the form of a single global emissions factor for each product. COC can also be calculated at the farm or regional scale. My calculations in Chapter 4, for example, use regional factors, and the tool in Chapter 5 calculates the COC of a specific farm.

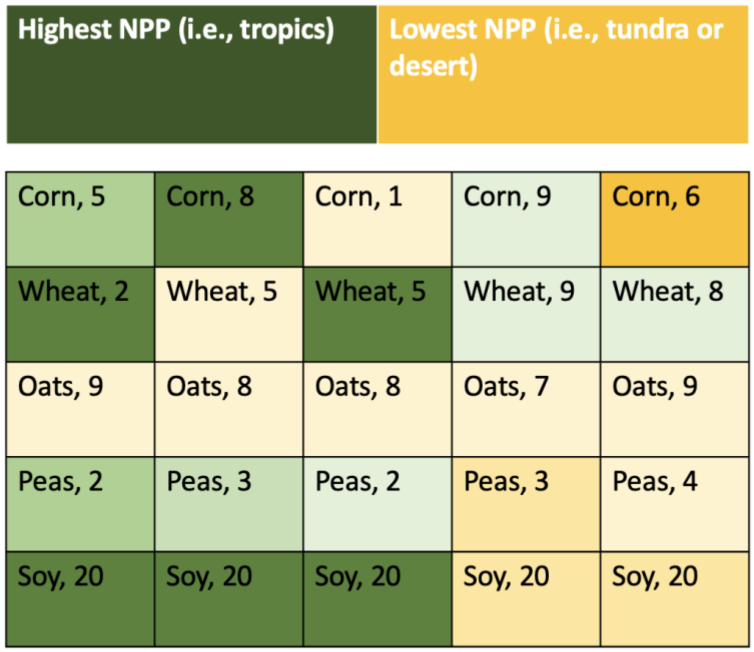

Figure 2. 4 Conceptual diagram illustrating how the global carbon opportunity cost is calculated with each box representing a country. The coloring indicates the Net Primary Productivity (NPP), where dark green is highest and dark yellow is lowest. The boxes contain different crops and their yields. Countries with high NPP and low yields would have the highest COC, and vice versa. (Source: Author)

To further demonstrate how the COC would be calculated at the farm level, consider a farm producing wheat where the average native potential vegetation across the farm is 100 tonnes of carbon (367 tonnes of CO_2) per hectare. The average yield of wheat is 5 tonnes (18 tonnes of CO_2) per hectare. The farm produces 2500 tonnes of wheat in total across 500 hectares. Therefore, the net carbon loss per hectare would be calculated as the difference between the native potential vegetation and the crop yield annualized over 30 years [(367 – 18)/30] for a value of 11.6 tonnes CO_2 per hectare. The annualized carbon loss per hectare is divided by the yield per hectare (5 t wheat/ha), to give a COC emissions factor of 2.32 tonnes of CO_2 per tonne of wheat per year. Figure 2. 5 illustrates the annualization of the COC. The red line shows the native potential vegetation, while the green line shows the crop yield. The difference between the two is the carbon loss per hectare, which is annualized (orange line).

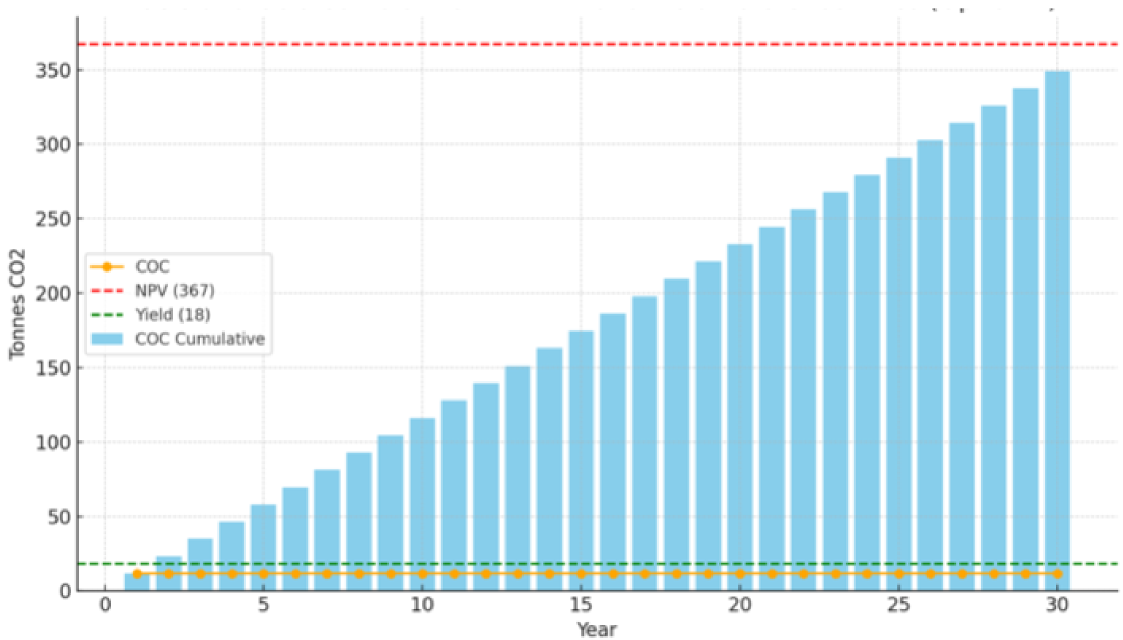

Figure 2. 5 Visualization of how the COC is calculated and allocated through annualization over 30 years. Native potential vegetation per hectare is shown in red, and crop yield per hectare is shown in green. The COC per hectare is the difference between the red and green lines, annualized over 30 years. The blue bars represent the accumulation of carbon costs over time. (Source: Author)

It is also necessary to understand how the COC responds to different decisions made by land managers. If the farm described above wants to increase its wheat production, it can either intensify production on existing farmland, or it can expand. The COC is calculated in Table 2. 1 below for those two scenarios using the values above. The table shows that increasing production through intensification reduces the COC per tonne of wheat, and in total. Expansion, on the other hand, does not affect the COC per tonne of wheat, but increases the total COC proportionately with the increase in land used.

Table 2. 1 Quantitative demonstration of the impact of intensification and expansion as national land use strategies on the COC calculation based on the scenario illustrated in Figure 2.5. Adapted from (WRI and WBCSD 2022a)

	a	b	c	d	e	f
	Area (ha)	Crop yield (t/ha)	Total wheat produced (t) (a x b)	Annualized C losses on wheat-producing land (t CO_2/ha)	COC per tonne of wheat (t CO_2/t wheat) (d/b)	Total COC of the farm (t CO_2) (c x e)
Baseline	500	5	2500	11.6	2.32	5800
Intensification	350	10	3500	11.0	1.10	3854
Expansion	700	5	3500	11.6	2.32	8120

Immediately following the publication of Searchinger et al. (2018), a comment was published seeking clarification on the original analysis (Muller 2018). In the comment, Muller argued the COC authors' statement that *"only increasing efficiency can allow the world to meet both food and climate goals"* does not account for the effect of potential changes in future demand, such as widespread shifts towards plant-based diets. This is not a fair interpretation if one takes efficiency to mean the number of people fed per hectare. Under such a definition, both intensification and reducing meat consumption would achieve that goal and would have lower COCs per kilogram of protein, whether plant- or animal-based. Muller went on to argue that shifting to less efficient ruminant systems, such as organic or grass-fed, would not necessarily increase food-related GHG emissions if global meat consumption were to decrease (Muller 2018). A reduction in production efficiency, however, cannot preempt changes in demand due to the risk of leakage, the emissions of which are estimated by the COC. Searchinger et al. (2018) argue in response that humanity and nature would be better-off if the world ate less meat *and* produced what remains more efficiently.

One year before the publication of the COC index, Muller et al. published a paper comparing organic and conventional agriculture, arguing that organic production systems offer a promising pathway to sustainable food systems (Muller et al. 2017). They found that, although global conversion to organic production would decrease yields overall, they proposed that reduced food waste and reduced consumption of animal products could counteract losses in yield. The COC explicitly separates the calculations for the effects of supply-side interventions such as improved efficiency and demand-side interventions such as shifting diets to incentivize both interventions at the same time. In an emissions inventory, for example, a grocery store could reduce its COC by sourcing less red meat, whereas a farm could reduce its COC by producing more food on the same amount of land. Simply put, the COC offers a biophysical alternative to other LUC calculations that has more transparent inputs, though these inputs can still be debated.

The concept of regeneration of native vegetation as a baseline, for example, has been criticized, with some arguing that biogenic carbon stocks are both dynamic and stochastic, thus efforts to estimate them into the future are inherently uncertain (Chiarucci et al. 2010). While the COC has been applied thus far in national and corporate accounting settings, a recent paper suggests that there is a risk of double-counting land-based removals, making it unsuitable for attributional product-level LCA in certain cases (Lehtilä and Leinonen 2025). Conversely, others have argued that establishing a baseline in attributional accounting is necessary to distinguish the effects of human activity from what would have otherwise occurred (Soimakallio et al. 2015).

The annualization method used in the COC calculation has generated further criticism, mostly through personal correspondence, thus these critiques are not published in the literature. The COC calculation applies a discount rate, a concept commonly used in economic decision making, on the grounds that *"carbon storage is lost quickly but crop production can continue* *indefinitely"* (Searchinger et al. 2018). Thus, the discount rate allows the impacts of clearing land to be allocated over some period, like the 20-year allocation period used for dLUC. Specifically, the COC calculation applies a 4% discount rate, which is higher than the 3.3% rate typically applied in mitigation valuation (Nordhaus 2017). The 4% discount rate is approximated by the 30-year annualization applied in the calculations in Table 2.1 for simplicity. Searchinger et al. (2018) justify their choice of discount rate based on the idea that a higher discount rate incentivizes more rapid near-term mitigation (Gerlagh and van der Zwaan 2004; Schoenmaker and Schramade 2024). The discount rate is ultimately a policy choice, and the authors note that COCs can be calculated with different rates, but it would not significantly influence decision-making. Chapter 5 explores the sensitivity of the discount rate in greater depth.

2.3.6 Land sparing and land sharing

Tangential to the debates around land use change metrics is the contrast between land sparing and land sharing. This binary refers to discourse within the land use policy and management sphere regarding whether a sustainable food future would be better achieved through intensification on existing agricultural land to "free up" land for carbon storage and biodiverse ecosystems elsewhere (land sparing), or through more extensive agriculture that is able to support more biodiversity on the same land relative to an intensive system (land sharing) (R. E. Green et al. 2005).

Land sharing is best described as a system in which nature and farming coexist on the same land (Balmford et al. 2015). This manner of agricultural production is favored by those who argue that mitigating negative externalities such as overuse of nitrogen fertilizers and pesticides should be prioritized (Fischer et al. 2008), or that a higher value should be allocated to on-farm biodiversity (Perfecto et al. 2005). In recent years, the agricultural climate mitigation policies for many countries, particularly in Europe, have tended towards visions of land-sharing with governments offering financial incentives for farmers to 'extensify' production to improve biodiversity or soil carbon sequestration (DEFRA 2018; European Commission 2024). The implications of this trend are critically examined in Chapters 5 and 6.

In some landscapes where soil health is poor and yields are low, land-sharing methods may be able to increase yields and improve biodiversity outcomes simultaneously (Castle et al. 2021; Jones et al. 2023; Kuyah et al. 2019). Additionally, some consider extensive grazing systems to be sustainable because some grazing land is not suitable for producing food for human consumption (Blackwell et al. 2024). However, evidence suggests that a widespread shift to grass-fed systems, which are often perceived as more sustainable and better for biodiversity, would significantly increase the overall environmental costs of livestock farming (Hayek and Garrett 2018).

In contrast, land-sparing argues that the best way to feed a growing population under biophysical constraints is to reduce pressure for further land use conversion (Godfray et al. 2010; Tilman et al. 2011). This can be achieved through a combination of 'sustainable intensification,' shifting diets, and reduced food loss and waste (Foley et al. 2011; Strassburg et al. 2014; Balmford et al. 2015). Several studies have applied spatially explicit optimization models to identify areas best suited to higher-yielding agriculture, and that have the greatest potential to support biodiversity or carbon storage to minimize trade-offs (Chapman et al. 2025; Hayek et al. 2024; Collas and Benton 2023b). The choice of metric in determining the sustainability of a land-sparing system also matters. One study explains that, while intensive systems may have higher environmental impacts per hectare, they can have substantially lower emissions when measured with intensity metrics (e.g. per kilogram of food) (Balmford et al. 2018).

Land-sparing fundamentally argues that improvements in efficiency can be linked to avoided deforestation or land use conversion elsewhere. Jevons' paradox, or the rebound effect, states that making something more efficient can increase demand for that product overall (Alcott 2005). In other words, increasing the efficiency of agricultural production may not directly alleviate pressure to convert more land. Rather, the improved economic viability of farming due to higher yields may instead incentivize more intensive farming over a larger area to maximize profit. Thus, improvements in efficiency must be coupled with better land governance, especially in areas at risk of deforestation, to avoid local leakage (Macedo et al. 2012).

The reality of these trade-offs leads me to ask: how can we achieve the simultaneous objectives of feeding a growing population while protecting existing ecosystems? Scaling up lower-yielding agriculture that supports on-farm biodiversity could significantly reduce the amount of food produced globally. On the other hand, intensification poses a threat to long-term sustainability. Thus, I argue the binary is false, with the best path forward existing in between two extremes. However, there is broad agreement that reduced consumption of land-intensive products is necessary to moderate land use competition and minimize the externalities of intensification (Foley et al. 2011; Clark et al. 2019; Springmann et al. 2018).

Ultimately, this concept reflects two opposing worldviews regarding the relationship between humans and nature, where the most desirable worldview is circumstantial (Loconto et al. 2020). Delivering an agricultural strategy that fairly and effectively meets climate, biodiversity, and food security objectives requires an understanding of relevant trade-offs and acknowledgment that the valuation of environmental outcomes can be subjective.

2.3.7 Important considerations in greenhouse gas and land use accounting

Chapters 4-6 in this thesis are built upon the scientific foundation of the metrics and concepts discussed throughout this literature review. I have argued that, to make effective decisions, we must be aware of what each metric is and, perhaps more importantly, is not measuring. The following reflections will be submitted as a Perspective to *Nature Climate Change,* with additional introductory text co-authored by Jimmy Jia and Myles Allen found in Appendix IV.

In GHG accounting, the concentrations of CO_2 and other long-lived pollutants in the atmosphere represent stocks, whereas emissions and removals of these GHGs are flows. Concentrations of short-lived pollutants, however, can be thought of as a flow if they do not accumulate beyond the period under consideration. In land use accounting, terrestrial carbon sinks such as forests and soils are stocks, and fluxes in these sinks due to land use change represent flows. Some metrics, such as GWP_{100}, have been described as 'stock' metrics, whereas metrics with a sliding window such as GWP* have been called 'flow' metrics. However, this framing is not necessarily helpful in conceptualizing what information a metric can communicate.

Some metrics arguably confuse stocks and flows. For example, if a herd of cattle has methane emissions declining by 0.3% per year, GWP* would allocate zero CO_2-we emissions. GWP, however, assigns a carbon cost to the cattle's ongoing emissions of methane. The size of that cost depends on the timescale chosen, which is ultimately a policy decision. GWP therefore treats methane emissions as contributing to a stock, even though they do not accumulate over the same time horizon as CO_2.

Similarly, dLUC measures the flows of biogenic carbon emissions and removals as they occur, and a scenario where land use remains constant for more than 20 years would be reflected as zero LUC emissions. However, this ignores the carbon stock that persists in the atmosphere due to historical LUC and continued anthropogenic uses of land. Conversely, COC assigns a cost to the fact that land is used as pasture rather than forest, and a portion of that cost is incurred every year depending on the discount rate chosen. This does not measure physical flows of GHGs, but rather the opportunity cost of the depleted stock due to anthropogenic land use.

One paper critiques GWP*, arguing that it is a model, rather than a metric (Meinshausen and Nicholls 2022). This is correct, and in fact, all 'metrics' assessed in this thesis are models that use activity data as an input and assess the impact of that data according to several value-based assumptions (J. Y.-J. Jia 2020). The difference between models and metrics can be understood in terms of the propagation of errors. Errors in models compound depending on the number of assumptions made or, in this case, emissions factors used, as emissions factors are inherently simplifications of physical processes (J. R. Taylor 2022). Conversely, statistical error of a metric (measured value) decreases with sampling. In other words, with more activity data or direct measurements, the measurement error decreases. Simply put, 'metrics' are used to calculate emissions in CO_2-equivalents using the following basic model:

$$Emissions = Activity\ Data\ x\ Emissions\ Factor$$

In this equation, activity data is a measurable value such as tonnes of fuel burned or heads of cattle, and the emissions factor represents a simplified model that approximates a chosen impact of the activity data on the environment. Each metric also makes certain assumptions regarding time and space, which in turn affect the comparability of results. To understand how the four metrics central to this thesis relate to one another, their inputs and assumptions are summarized in Table 2. 2.

Once metrics are understood as models with inputs, outputs and assumptions, it is then possible to explore what those models can and cannot do. From Table 2. 2, the metrics can be compared in many ways. Note the split between metrics that convey impacts based on an absolute versus relative baseline. GWP_{100}, for example, conveys the integrated radiative forcing of emissions over a 100-year time horizon compared to a baseline scenario in which those emissions did not occur. Conversely, GWP* measures the contribution to warming of emissions relative to the level of emissions 20 years ago.

This distinction is exemplified in the case of ongoing discussions around methane mitigation in New Zealand. Agricultural methane emissions make up approximately half of New Zealand's national GHG emissions using GWP_{100}. Under GWP*, however, New Zealand would be able to claim to have reached net zero emissions relative to a recent baseline through modest reductions in methane emissions. Controversially, this ignores that New Zealand's historical contribution prior to the arbitrary base-year is significant.

Goodhart's law states that *when a measure becomes a target, it ceases to be a good measure* due to the tendency of fallible actors to game the system. In an anecdote describing perverse incentives known as "The Cobra Effect," a country facing an infestation of snakes has a goal to reduce the number of snakes. The measure chosen to track progress on solving this issue is the number of dead snakes. To set a target, the government offers a bounty for dead snakes. However, rather than incentivizing citizens to hunt existing snakes, it is easier to reap the benefits by breeding and killing new snakes (Siebert 2002).

In the case of New Zealand, net zero has been set as a target, though the parameters of success are left undefined. Rather than setting metric-agnostic targets to directly address the problem of GHG emissions, actors can select metrics that make it easier to meet the target. This disincentivizes the pursuit of further action to help the rest of the world achieve net zero, which is ultimately necessary. It can therefore be argued that New Zealand still has a responsibility to address and undo its historical contribution to warming, and national net zero targets have thus ceased to be a good measure, as Goodhart would say.

This argument can be further explored through the distinction between the level of warming a country has caused and its current rate of warming. An activity contributes to the level of warming and the rate of warming, though only some activities contribute predictably to both. Burning fossil fuels, for example, contributes to both in a predictable and similar way. Cattle herds, however, do not contribute to the level and rate of warming in the same way. The existence of a cattle herd contributes to the level of warming, whereas management decisions for the herd determine the rate of warming. If the global target is not only to stop warming, but to stop it at as low a level as possible, separate targets would be needed for both the level of warming and the rate of warming.

An economic comparison using capital and income would come to the same conclusion. In an economically efficient world, one would identify the best way to increase both money in the bank and the rate of income with separate targets. One could get a higher-paying job to increase income and stop eating at restaurants to increase capital.

When it comes to climate change, confusion arises with the notion of "common but differentiated responsibilities," which introduces nonlinearity in incentives to act. If a country has met its obligation by meeting its own net zero target, as defined by its own terms, that country might argue it does not need to reduce emissions any further. This is seen with other forms of environmental damage, such as in the case of zero deforestation commitments. If a country is not actively deforesting, they are compliant and do not need to act, even though they may have deforested hundreds of years ago, beyond the temporal boundary considered for the commitment.

When framed in this way, there is no such thing as “good enough” in the case of climate mitigation. Rather, it is important to set boundaries to ensure that a target remains a good measure, or recognize when multiple targets are necessary to achieve a global objective such as minimizing warming. This critical examination of the assumptions and boundaries behind commonly used metrics explores how a concept with scientific value can lead to targets with perverse incentives.

Table 2. 2 Comparison of the metrics assessed in this thesis based on the activity data required for the calculation, temporal and spatial boundaries, units, and the assumed baseline

Metric	Activity Data	Emissions Factor	Temporal Boundary	Spatial Boundary	Units of Emissions	Baseline
GWP	Quantity of emissions of each GHG per year	Radiative forcing of a non-CO_2 GHG relative to that of CO_2 (coefficient)	20, 100, 500, etc. years in the *future*	Used at any system boundary (national, corporate, global, etc.)	CO_2-equivalent emissions	Zero emissions (absolute)
GWP*	Quantity of emissions of each GHG per year with at least 20 years of historical data	$128(E_t) - 120(E_{t-20})$ for short-lived GHGs (coefficient)	Impact on present temperature, where the 'present' is defined by a 20-year window	Used at any system boundary (national, corporate, global, etc.)	CO_2-warming equivalent emissions	Recent activity over the last 20 years (relative)
COC	Quantity of land-based product	Annualized total carbon loss per product globally (kg CO2 per kg product)	Either looking back (historical carbon loss) or looking forward (foregone sequestration)	Typically global, can be calculated regionally	CO_2	No human activity (absolute)
dLUC/sLUC	Quantity of land-based products delineated by country of origin	Annualized *recent* carbon loss per product, jurisdictionally (kg CO_2 per kg product per country)	Annualized forest carbon stock changes over previous 20 years, no consideration for earlier stock changes	National or jurisdictional	CO_2	Recent land use change over the last 20 years (relative)

2.4 Agricultural emissions accounting tools and frameworks

There are many methodologies and tools available to measure and monitor agricultural emissions as countries and companies try to set and achieve climate mitigation targets (Colomb et al. 2013; WRI and WBCSD 2022b). This section therefore outlines existing emissions accounting frameworks for both national and corporate system boundaries and provides an assessment of existing tools. Figure 2. 6 presents a high-level illustration of corporate and national emissions accounting systems, and how they relate to each other. The following sub-sections explore each component in greater detail.

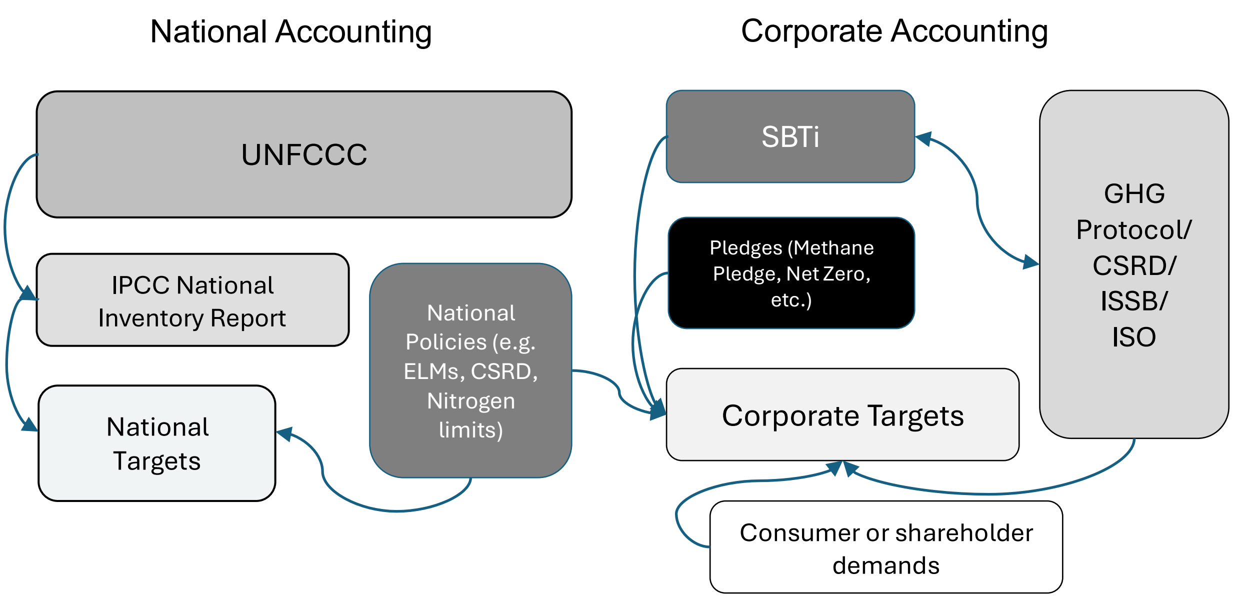

Figure 2. 6 Conceptual diagram illustrating the key components and interactions for national and corporate emissions accounting. (Source: Author)

2.4.1 National emissions reporting

Assessment reports produced by the IPCC require member states to submit information that can be used to calculate national emissions. These assessments are then used to track progress towards the objectives set out by the UNFCCC, such as those of the Paris Agreement. Countries submit annual National Inventory Reports (NIRs) to the IPCC following a standardized reporting format.

The NIRs are structured by sector, where Agriculture is considered to be a separate sector from Land Use, Land Use Change, and Forestry (LULUCF), though this thesis often refers to them jointly as the 'land sector.' The IPCC's Guidelines for National GHG Inventories outlines how each emissions category should be reported, the types of data required, and how to improve data quality (IPCC 2019). In the Agriculture sector, the following emissions categories are included in the NIR: enteric fermentation, manure management, N_2O from nutrient application, liming, urea application, and some categories not relevant to this thesis (e.g. burning of agricultural wastes and rice cultivation). Emissions from the production of imported inputs such as nitrogen fertilizers or animal feed are counted in the country where production occurs, rather than where they are used, a convention that has been criticized for its tendency to cause leakage (Peters 2008). Countries use the results of the NIR process develop national targets based on the level of mitigation required to meet climate targets and other obligations such as the national objectives outlined in Chapter 2.2.4.

2.4.2 Corporate emissions reporting

Corporate emissions accounting is arguably more complex than national reporting for several reasons. First, corporate supply chains are themselves complex and are oftentimes opaque. In other words, companies often cannot trace the geographic origin of their inputs, let alone collect data required to estimate emissions from production processes (Fripp et al. 2023). To make certain sustainability claims, companies often rely on certifications issued through one of several chain of custody models. These certifications are most used in corporate zero-deforestation claims for commodities linked to deforestation such as cocoa or soy. Chain of custody models range from ‘Identity Preserved,’ which requires the deforestation-free product to remain separate and known throughout the supply chain, to the ‘book and claim’ model in which certificates can be bought from an entity producing zero-deforestation commodities regardless of whether that product ever enters the company’s supply chain (WRI and WBCSD 2026; ISO 2020). Given the lack of traceability in corporate supply chains, companies typically rely on global or national emissions factors that cannot capture the effects of changes in farming practices that might result in lower emissions.

Second, corporate reporting does not have one single standardized accounting framework akin to the NIR for country-level accounting. Rather, there is an interconnecting web of standards and guidance that companies can voluntarily utilize. As shown in Figure 2. 6, corporate reporting is often informed by the Greenhouse Gas Protocol (GHGP) sectoral standards, which instruct companies on how to report emissions across Scopes 1, 2, and 3. Scope 1 emissions occur within a company’s operations. For example, a beef farm’s Scope 1 emissions would include enteric fermentation, manure management, etc. Scope 2 emissions result from the consumption of energy within the operational boundary. Finally, Scope 3 emissions are those which occur beyond a company’s operations, but within their supply chain. For example, the Scope 1 emissions of the farm would be included in the Scope 3 emissions of the grocery store selling the beef.

Once emissions are reported, the Science Based Targets initiative (SBTi) provides sector-specific guidance on how to set targets that are aligned with climate and ecological science. The SBTi’s Forest, Land and Agriculture (FLAG) guidance states that food and agriculture companies must reduce supply-chain emissions by at least 72% by 2050 to be in line with the Paris Agreement (SBTi 2023). Note that this guidance does not require companies in the agriculture sector to reach net zero. Additionally, the achievability of this target for a supply chain with only arable crops compared to a ruminant supply chain is vastly different, particularly given the differences in GHGs involved, as discussed throughout Chapter 2.3. Chapter 6 explores the implications of this target, as well as the net zero concept in general, for the ruminant sector.

In early 2026, the GHGP released the Land Sector and Removals Standard, which is designed specifically for companies producing, buying, and selling land-based commodities including livestock products (WRI and WBCSD 2026). This standard is the first of its kind to mandate reporting of land use beyond conventional dLUC or sLUC indicators. Companies using the standard must report either 'land occupation' calculated using yields or COC (see Chapter 2.3.5). The requirement to use these indicators supports one of the key arguments made within this thesis—that attributional emissions inventories benefit from the consideration of a counterfactual based on the natural processes that would have occurred in the absence of human activities (Soimakallio et al. 2015).

The GHGP and SBTi are only two examples of a myriad reporting and target-setting standards to which companies may adhere. The International Organization for Standardization (ISO), for example, sells best-practice guidance for various aspects of industrial activities including health and safety as well as environmental management. ISO 14064 specifically relates to GHG and removals accounting, projects, and verification. Evidence in the literature suggests that this standard is aligned with the IPCC Good Practice Guidance (Bastianoni et al. 2014) and earlier GHGP standards (Gao et al. 2014), though alignment with the recent GHGP Land Sector and Removals Standard has not yet been examined.

Similarly, the International Sustainability Standards Board (ISSB) is yet another standardization body with the aim of facilitating corporate sustainability-related financial disclosures (Rimmel et al. 2025). The elements of the ISSB extend beyond GHGs alone to include corporate impacts on nature, which are less easily quantified (G. S. Smith et al. 2024).

Some corporate reporting standards are regionally specific, and adherence is mandatory for companies operating in the region. To give an example relevant to this thesis, the Corporate Sustainability Reporting Directive (CSRD), part of the European Green Deal, requires that companies report on both their impact on the environment and the financial risks those impacts might cause (Hummel and Jobst 2024). Similarly, the EU Deforestation Regulation (EUDR) introduced in 2023 mandates that deforestation-linked commodities available on the EU market, including beef, are not contributing to deforestation (Commission Notice – Guidance Document for Regulation (EU) 2023/1115 on Deforestation-Free Products 2025). To be compliant, companies must be able to trace the products in their supply chain with a geographic resolution sufficient to claim that their sourcing region is at a "low risk" of deforestation (European Commission 2025b).

Finally, public corporations in the agriculture sector are beholden not only to legal sustainability reporting, but also customer and shareholder demands in addition to voluntary pledges or certification schemes. This confluence of corporate responsibilities has proved to be an obstacle in the alignment of industry objectives and regulatory obligations (Prasanna et al. 2025). We explore these tensions through interviews with corporate stakeholders in Chapter 6.

2.4.3 Agricultural emissions tools

To meet the corporate emissions-reporting needs detailed in the previous section, several accounting tools have been developed by various corporate and academic entities. These tools typically employ LCA methodology and a user-friendly interface for companies or land managers to input information about their practices. As part of the GHGP Land Sector and Removals Guidance process, I developed a list of over 100 land sector accounting tools and resources (WRI and WBCSD 2022b). Table 2. 3 below presents an adapted excerpt of tools from this list that are relevant to this thesis, with some additional more recent resources added. The original research in Chapters 4 and 5 builds upon many of these tools to develop new models that address certain weaknesses discussed in Chapters 3.3 and 3.4.

Table 2. 3 List of existing agricultural emissions accounting tools. (Adapted from WRI and WBCSD, 2022b, originally compiled by the author)

Organization / Author	Resource Name	Type of Resource	Availability	Updates	Description	Sector	Country / Region	Link
Blonk Consultants	Direct Land Use Change Assessment Tool (2022)	Tool	Fee to access	Updated at some frequency	A calculation tool with associated data for estimating land use change for three scenarios; 1) Country of origin and land use is unknown 2) Country of origin is know but land use is unknown 3) Country of origin and land use are known	Agriculture	Global	https://blonksustainability.nl/tools/LUC-impact
Cool Farm Alliance	Cool Farm Tool	Tool	Partially available, fee for full access	Updated at some frequency	Free for growers, online tool that tracks GHGs, biodiversity impacts, water, and supply chain management	Agriculture	Global	https://coolfarmtool.org/
Ecoinvent	Ecoinvent	LCA Database	Partially available, fee for full access	Updated at some frequency	Extensive database of LCA impacts of products and processes. Limited guest version available for free, full version requires a license	General (all land sectors)	Global	https://ecoinvent.org/the-ecoinvent-database/
FABLE consortium	FABLE Calculator	Tool	Free	Released in 2020, updated at some frequency	Consequential Excel-based tool which simulates future food system scenarios in terms of impacts on emissions, food security, and biodiversity	Agriculture	Global	https://fableconsortium.org/tools/fablecalculators/
Food and Agriculture Organization	Ex-Act	Tool	Free	Most recent version (v9) released in 2022	Consequential calculator tool that estimates the impact of different agricultural interventions on emissions	General (all land sectors)	Global	https://www.fao.org/in-action/epic/ex-act-tool/suite-of-tools/ex-act/es/
Food and Agriculture Organization	GLEAM	Tool	Free	Most recent version (v3) released in 2024	Attributional livestock emissions and land use model which can also run consequential scenarios to simulate changes in practice	Agriculture	Global	https://www.fao.org/gleam/en/
HESTIA.earth	HESTIA	LCA Database	Free	Updated very frequently	Extensive open-source harmonized LCA database of agricultural products, including GHG emissions and 16 other resource uses	Agriculture	Global	https://www.hestia.earth/
SAC Consulting	Agrecalc	Tool	Partially available, fee for full access	Updated at some frequency	Agrecalc is a carbon footprint tool developed by SAC Consulting together with SRUC researchers. It enables farm enterprises to identify and measure emissions, benchmark key performance indicators, identify mitigation strategies and monitor improvements.	Agriculture	Scotland	https://www.agrecalc.com/

2.5 Summary and research gaps

The scientific origins of GHG and land use metrics, in terms of both why they were developed and the purpose they have come to serve, form the conceptual foundation of this thesis. Table 2. 4 summarizes the concepts included in the literature review, identifies the research gaps, and explains how the original research of Chapters 4-6 addresses those gaps.

With respect to GHG metrics, the literature review raises the question of whether the assumptions built into GWP_{100} are appropriate for the range of applications for which it is used. In reference to the abstract at the start of this chapter, if the objective of an accounting system is to effectively serve as an emissions trading system, then annual 'pulse' metrics such as GWP_{100} are necessary. If a metric is being used to inform decisions about the future, however, other accounting methods become useful as well. For example, if the goal is to achieve peak warming and minimize increases in global temperature, it is helpful to use a metric that effectively communicates the impact of a decision on warming.

The evolution of land use metrics similarly brings about questions regarding the effectiveness of conventional metrics across broad applications. I argue that the information provided by dLUC or sLUC—a quantification of recent LUC emissions associated with a product from a specific region—is of limited use. While understanding the amount of recent deforestation within a supply chain is useful for corporate inventories or deforestation-free supply chain claims, these metrics alone are insufficient to enable forward-looking strategies that minimize global land use competition.

The overarching controversy around metrics is that some result in a larger number, which has been interpreted as a representation of greater guilt or responsibility. But there are many reasons why countries or companies make decisions, and guilt is not necessarily one of them. The inclusion of COC, for example, assigns countries and companies more blame, thus there is resistance to using the metric. In contrast, GWP* makes the emissions of ruminant herds in the Global North appear smaller, therefore it has garnered favor in some circles and disdain in others.

Instead of asking how metrics can be chosen to minimize perceived emissions and responsibility to act, I argue that the path forward should utilize whichever indicators incentivize solutions aimed at addressing the global impacts of agricultural production. Over the next several chapters, I will build on the existing literature on metrics and land use policy to ultimately suggest changes to emissions accounting frameworks such that they more effectively inform decisions based on the physical realities of climate and land use change.

Table 2. 4 Summary of key literature review topics, the research gap, and how the original research in this thesis contributes new knowledge.

Concept	Summary	Research gaps	Contribution of original research
Environmental impacts of cattle (Chapter 2.2.1-3)	Sources of emissions in ruminant farming, and options to mitigate them	Relative impact of different emissions reduction strategies and technologies, and the effect of emissions accounting decisions	**Chapter 4** projects the effects of several mitigation pathways using different accounting frameworks to highlight the relative effects of different interventions.
National land use strategies (Chapter 2.2.4)	UK and EU land use policy, and the roles of different stakeholders	The potential contribution of national land use strategies to the global objective of farming within planetary boundaries	**Chapter 5** quantifies possible trade-offs between yield and biodiversity/carbon storage based on ongoing UK land use policy developments. **Chapter 6** qualitatively examines how stakeholders in Europe conceptualize sustainable ruminant systems and define net zero.
GHG metrics (Chapter 2.3.1-3) and land use metrics (Chapter 2.3.4-6)	Origin, physical science, and assumptions behind different GHG and land use metrics, and how they are used	Policy implications of metric choice in the context of ruminant mitigation	**Chapter 4** evaluates different metrics on the basis of how they influence mitigation incentives. **Chapter 6** explores stakeholder understanding of these decisions in the context of a net zero ruminant sector.
Corporate and national emissions accounting frameworks (Chapter 2.4)	An overview of how corporate and national entities report emissions and set targets	The extent to which corporate and national accounting frameworks are aligned with each other, and facilitate effective mitigation strategies	**Chapter 6** uses stakeholder interviews to identify root causes of misalignment in reporting and mitigation incentives, and makes recommendations for facilitating more collaborative efforts.

Chapter 3: Methodology

Across the three papers, I apply various qualitative and quantitative methods to investigate the interdisciplinary issues around the sustainability of agriculture and the policy implications of decisions around metrics. Because the empirical chapters of this thesis contain descriptions of the methods used, this chapter explains the theory underpinning the original research, justifies each methodological approach, and discusses relevant research ethics.

3.1 Research paradigm

The methodological choices made in this interdisciplinary mixed-methods thesis draw upon critical realism, a philosophy of science based on the work of Roy Bhaskar, which posits that reality exists independently of what can be directly observed (Bhaskar 1975, 1979). To give an example relevant to the topic at hand, global land use change for agricultural expansion *is* occurring, although the extent to which changes in agricultural production in the UK are responsible for land use change elsewhere may be difficult to objectively discern.

Research paradigms are often situated as either positivist, a view in which reality is objective and replicable, or constructivist, wherein reality is entirely socially constructed and qualitative methods are favored (Guba and Lincoln 2005). Critical realism, on the other hand, makes space for the existence of an objective reality, while recognizing that it can be experienced subjectively (Edwards et al. 2014). I therefore draw on critical realism to acknowledge that agriculture has an environmental impact, which we can try to measure empirically, but the decisions we make regarding what we measure and how we measure it can influence how that impact is perceived and how mitigation strategies are rationalized.

This ontological perspective supports the use of a mixed-methods approach to explore measurable reality, while also using qualitative methods to understand the underlying social mechanisms behind observable events (Edwards et al. 2014). In the context of policy research specifically, critical realism argues that quantitative methods alone cannot sufficiently lead to effective outcomes (Cartwright and Hardie 2012). As such, I combine quantitative modeling with qualitative stakeholder interviews to unpack these social mechanisms and diverse interpretations of reality in the context of agricultural impact mitigation.

To further justify my decision to ground the methodology in critical realism, I present what the foundational assumptions could have been had I applied an alternative paradigm, and I explain why those options are not suitable. A positivist approach might assume that there is an optimal mitigation pathway and would model the impacts of that pathway alone. This paradigm ignores that actors are fallible, and that an optimal pathway is unlikely to be implemented seamlessly. Conversely, a constructivist approach would assert that future mitigation outcomes can never be known with certainty due to the variability in perspectives and objectives of actors. Critical realism combines elements of both approaches. This paradigm facilitates the consideration of a wider range of possible mitigation outcomes and scenarios, while accounting for the subjectivity and complexity of actors' decision-making.

While critical realism provides an explanatory framework for identifying underlying mechanisms and structures, my research paradigm is also informed by elements of pragmatism, particularly in its emphasis on the practical utility of knowledge for real-world policy contexts (Maxwell 2023; Morgan 2007, 2014). Pragmatism supports methodological flexibility and the idea that research should be evaluated, at least in part, by its usefulness in informing decisions and guiding action

(Kaushik and Walsh 2019; Weaver 2018). This thesis applies pragmatism in that I select research methods that are best suited to generate a useful answer to each research question.

3.2 Quantitative data collection

Chapters 4 and 5 utilize quantitative data from a range of sources. The scenario analysis employed in Chapter 4 is justified in Chapter 3.3, and Chapter 3.4 rationalizes the approach used to develop a novel calculator to compare the direct and indirect effects of farmer incentives. This section maps the various sources of quantitative data, and outlines the assumptions made to practically address the research questions of this thesis.

3.2.1 Setting a baseline for UK cattle emissions

The conventional methodology for establishing a baseline for agricultural impacts would be to conduct a Life-Cycle Assessment (LCA). Environmental LCA measures a wide variety of impacts associated with a product or system, and typically includes the impacts of producing inputs, transportation throughout the supply chain, and sometimes disposal (Hellweg and Milà i Canals 2014). These processes are assessed not only for their contribution to GHG emissions, but also other environmental impacts such as water use, water pollution, and toxicity (De Bruijn et al. 2002). These assessments can provide a standardized comparative basis for the sustainability of products (Curran 2013). In the context of agriculture, LCA is generally conducted at the farm or product level with values often reported per unit area or unit mass of output (Fan et al. 2022).

Chapter 4 draws on these LCA principles to establish a baseline of greenhouse gas and land use emissions associated with cattle production in the UK. However, farm-level data is not readily available across the entire country, and this thesis is primarily concerned with the implications of metric choice on the incentives for the national livestock sector to mitigate GHG and land use impacts specifically. For those reasons, I must bring in other methodological concepts to best address Research Question 1.

Chapter 4 applies the concept of ‘operational control’ to justify setting a system boundary that includes the upstream production of inputs such as feed and fertilizers but omits downstream impacts such as transportation and disposal. Because this paper explores the effects of on-farm interventions, I include only the impacts that can be mitigated up to the farm gate. There is also a basis in the LCA literature specific to agriculture for delineating the system boundary to include emissions categories up until the farm gate, as opposed to a ‘cradle-to-grave’ approach (Caffrey and Veal 2013; G. Haas et al. 2000; Tuomisto et al. 2012). Therefore, my approach does not fit neatly into conventional LCA methodology, but rather is pragmatically constructed to analyze the effects of interventions on specific components of a more traditional LCA. Figure 3. 1 illustrates the differences between the operational control boundary utilized in this thesis and a more conventional LCA system boundary.

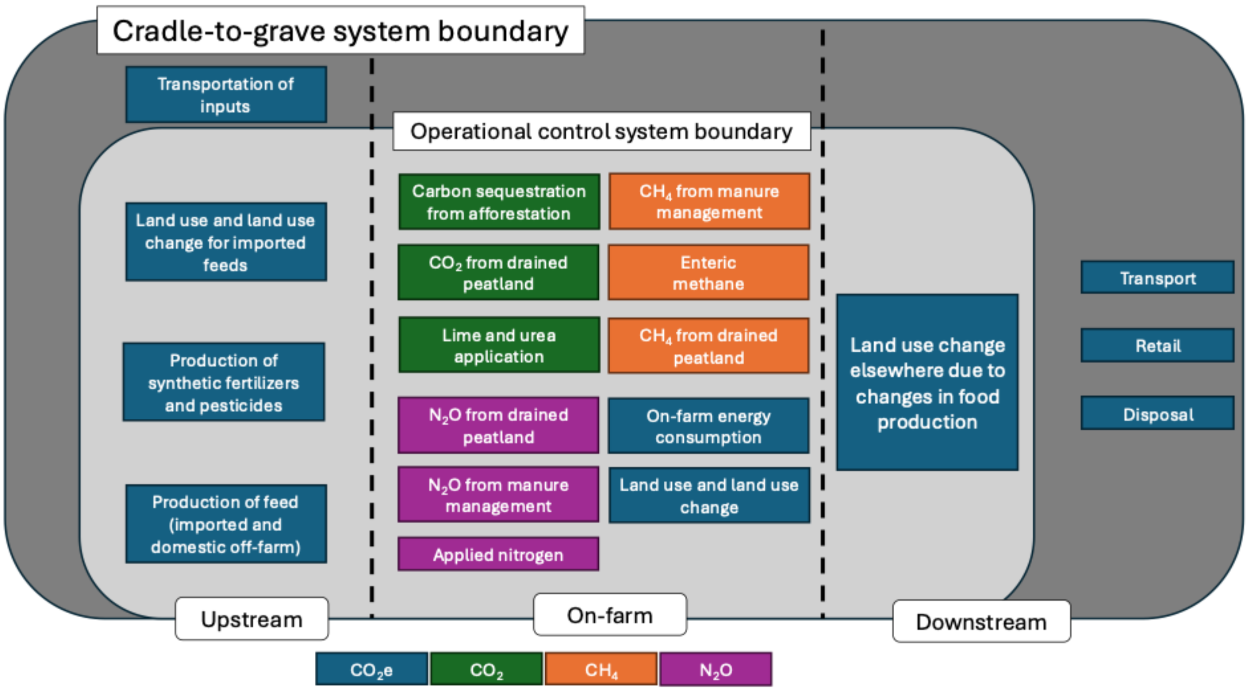

Figure 3. 1 Illustration of the operational control, or 'cradle-to-gate,' system boundary utilized across this thesis, compared to the cradle-to-grave boundary often used in LCA. The colors indicate whether the emissions category is disaggregated by GHG or reported as an aggregate in CO_2e.

To establish a baseline for the GHG and land use emissions from UK cattle production, Chapter 4 reproduces the relevant production emissions established in the National Inventory Report (NIR), which include enteric methane, manure management, and applied nitrogen (IPCC 2019). However, given the operational control approach, I calculate emissions from other activities that are not typically included in national reporting, such as emissions from the production of pesticides and synthetic fertilizers using data from the Food and Agriculture Organization (FAO) (FAOSTAT, n.d.). Furthermore, some categories, such as applied nitrogen, are only reported as a national aggregate, rather than by livestock type. Thus, I use data from the Agriculture and Horticulture Development Board (AHDB) to allocate emissions from these other sources to cattle production alone (AHDB 2023b).

Calculating land use emissions for cattle alone requires similar allocation mechanisms. Feed use is reported by the AHDB either by feed type, or by animal type, but not by feed type for each animal type. Thus, a series of assumptions outlined in the Methods section of Chapter 4 allows for the establishment of a baseline for the consumption of feed and forage for cattle.

Therefore, the quantitative approach to Chapter 4 combines a foundation of LCA elements with a more pragmatic operational control-based system boundary to facilitate meaningful analysis of the climate and land use implications of different farm-level interventions.

3.2.2 Systematic review

A systematic review is a method that synthesizes existing research on a given topic, though it is distinct from a meta-analysis in that it does not use any statistical methods (Littell et al. 2008). In Chapter 5, I conduct a systematic review of LCA and meta-analysis studies that estimate the effect on yield of shifting to arable farming practices incentivized in the Environmental Land Management schemes (ELMs). These practices include conversion to no-till, organic, or the use of cover crops (DEFRA 2023b).

In the literature, there are many LCA studies and meta-analyses that analyze crop yields around the world. However, the review conducted for Chapter 5 focuses on extracting UK data points from this literature. For example, one widely-cited meta-analysis examines LCA data for over 38,000 farms (Poore and Nemecek 2018). However, only four studies out of those 38,000 contain yield data from the UK comparing conventional and alternative farming methods. I take this approach to generate a range of potential yield effects at the national level. Though relatively little data was found through the review process despite the proliferation of agricultural LCA in the literature, the exercise nevertheless provides useful insights into the possible effects of ELMs incentives and highlights the need for more comparative yield data as an area for future research in the UK.

3.3 Scenario analysis

Initially developed as a more sophisticated method for financial forecasting, scenario analysis places emphasis on producing a probabilistic range of possible futures, as opposed to predicting a single future (Huss 1988). In the field of climate science, scenario analysis is a useful tool to explore the implications of a range of possible policy decisions or technological developments (Moss et al. 2010). For example, the Shared Socioeconomic Pathways are used in the IPCC Assessment Report process to explore different climate mitigation scenarios (van Vuuren et al. 2012).

Chapter 4 uses scenario analysis to explore the effects of GHG and LUC metrics used to quantify the impact of ruminant agriculture in the UK under four stylized mitigation scenarios. Another study, published around the same time as Chapter 4, compares GWP_{100} and GWP* in the context of European scenarios for agricultural emissions mitigation, but does not consider LUC or end-of-century climate impacts (Zerbe et al. 2025). Using these stylized scenarios, the paper examines each metric based on which interventions it incentivizes, and the strengths and limitations of its utility in climate mitigation. As such, the discussion addresses misconceptions around the more novel metrics, and offers guidance for decision-making regarding metric choice.

3.4 Development of a new calculator

All models are wrong, but some are useful. This aphorism, attributed to statistician George E.P. Box, acknowledges that modeled systems fail to accurately reflect all facets of a real system.

This is especially true in the case of carbon calculators, which are models designed to estimate the emissions of a product or operation. These models often rely on simplified assumptions of complex biological and geological systems. However, simple models based on the fundamental principles of a system can offer intuitive insights into the variables and interactions in question (Messé et al. 2025).

There are several agricultural emissions calculators available, which are summarized in Chapter 2.4.3. Following a thorough review of all available tools, it was deemed necessary to develop my own to answer the specific research questions for Chapter 5. Most agricultural carbon calculators use attributional accounting, measuring the footprint of a farm and allocating the emissions to the various products. The Farm Productivity Evaluation Tool (FarmPET) created for this thesis, however, is a consequential calculator that assesses the impact of an intervention or decision. Like scenario analysis, consequential calculators are useful tools for understanding the implications of a policy or decision into the future.

I also note that the quality of any calculator's results is linked to the quality of data used as inputs. As I discuss in Chapter 3.2.2, I found very few studies providing relevant data through my systematic review, which constitutes a limitation that I consider in the interpretation of the calculator's results.

3.5 Qualitative data collection

For the third paper (Chapter 6) of this thesis, I conducted 41 stakeholder interviews in four European countries to explore the perspectives of key stakeholders across corporate, farming, governmental, and academic groups. These interviews were conducted from March through July of 2025. The majority were held in-person, with around one-quarter conducted using Microsoft

Teams. This section justifies the use of stakeholder interviews as a method in social science research and explains the use of purposive sampling.

3.5.1 Stakeholder interviews

Analysis of stakeholder perspectives as a social science method emerged from business management science to explore relationships among actors pertaining to power and influence in a broader socio-political context (Brugha and Varvasovszky 2000). A stakeholder can be defined as any group or individual who can affect or is affected by the achievement of an organization's purpose (Freeman 2010). In the context of this thesis, 'organizations' are corporate and government entities, and their collective purpose is to achieve sustainability goals in their supply chain or country, respectively. Thus, the scope of Chapter 6 was developed to encompass the groups whose actions can affect the development and execution of decarbonization strategies for ruminant agriculture, or whose interests would be affected by said mitigation interventions. In this case, four key stakeholder groups were identified: policymakers, corporate representatives, researchers, and farmers. The interviews were conducted in Denmark, the Netherlands, Ireland, and the UK. These countries were chosen due to distinct contentions and ongoing debates in national and corporate agricultural mitigation policy (see Chapter 2.2.4).

Given the range of backgrounds of the interviewees, both professional and personal, semi-structured interviews were deemed most appropriate to allow for questions that explore the participants' lived experiences and expertise with flexibility and pragmatism (Galletta and Cross 2013). While the form of the interviews was open-ended with follow-up questions constructed on the spot, semi-structured interviews require a great deal of preparation to tailor an interview structure to the national context and professional interests of each participant (Wengraf 2011). Prior to each interview, I familiarized myself with relevant publicly available material regarding the participant's experience with the topic at hand, as well as national and corporate context to prepare individualized questions about said perspectives. Appendix III contains a high-level interview outline that I personalized for each participant.

3.5.2 Purposive sampling

The interview participants were recruited using purposive sampling, which involves careful curation of non-random individuals to study a specific phenomenon such as, in this case, the development of net zero strategies in the ruminant sector (Silverman 2022). Once the countries and stakeholder groups had been determined by the author team, I conducted a mapping exercise in which I developed a list of possible individuals or institutions for each country and stakeholder group that would have relevant insights or experiences to justify participation in this study. For each country-stakeholder group, I listed three or four individuals to contact, with the aim of successfully conducting at least one interview per group.

My supervisors and I personally invited potential interviewees within our own networks in the UK. When necessary, I collaborated with in-country partners to facilitate recruitment in Denmark, Ireland, and the Netherlands. Specifically, I relied on employees of Hilton Food Group (HFG) in these countries, as well as contacts within affiliated research institutions to set up interviews on my behalf. I made a concerted effort to interview enough stakeholders to include a representative range of perspectives within each group. For example, one would expect that the perspective of an organic hobby beef farmer would differ significantly from that of an intensive dairy farmer. However, the representation of interviewees was likely affected by the fact that many interview requests were sent by HFG representatives. Some organizations may not feel comfortable participating in research funded by a large meat processing corporation, which would limit the inclusion of certain perspectives. Conversely, the perspectives among institutions within HFG's network are likely in alignment, which may have excluded voices that are more critical of the meat processing industry.

The representativeness of the final participant list was limited due to several factors. Primarily, time constraints both for conducting interviews and analyzing the data limited the number of participants and thereby limited the range of perspectives. In terms of recruiting interviewees, I found that government stakeholders were most reluctant to participate in this study, mainly due to constraints on their time. Of the academic and non-profit researchers invited, some declined because they did not consider themselves to have sufficient expertise on the topic. Lastly, farmers were the most difficult group to reach in-person due to the rural location of their farms. In Denmark and the Netherlands, they were also more likely to require a translator. For these reasons, the farmers included in the study tended to be already engaged, either with companies like HFG or with special interest groups. Thus, they had more informed views around sustainability and less engaged farmers in some countries were unintentionally excluded.

3.6 Qualitative data analysis

Following the completion of all stakeholder interviews, I conducted data-led (inductive) thematic analysis using NVivo software. Data-led thematic analysis is a flexible framework that allows themes to emerge from the data itself, as opposed to theory-led analysis, which applies a theoretical framework at the outset of the coding process (Ahmed et al. 2025).

The thematic analysis process was guided by critical realism (see Chapter 3.1) in that the objective of the analysis was to understand causal mechanisms and social constructs underpinning interviewees' experiences and opinions (Danermark et al. 2019; Fryer 2022). The design and analysis of Chapter 6 was guided by the five-step approach to critical realist data-led thematic analysis outlined in Fryer (2022). Table 3. 1 below outlines those steps and how they have been applied.

Table 3. 1 Methodological steps for applying critical realism to thematic analysis based on Fryer (2022), and application of these steps in Chapter 6 of this thesis.

	Methodological Step in Fryer (2022)	**Application in Chapter 6**
1	Develop causal research questions	The questions were developed to understand the experiences of stakeholders with developing and executing mitigation strategies, and the socio-economic factors contributing to the construction of those views.
2	Familiarize yourself with the data	I took handwritten notes and kept a field diary as I conducted the interviews to summarize the data as it was collected. As I cleaned and anonymized the data, I also highlighted quotes that stood out as relevant. I then read through the transcripts a second time to conduct the coding.
3	Apply, develop, and review data-led codes	From the field diary notes, I developed preliminary descriptive codes prior to the start of the formal coding process. These codes were refined and consolidated, and new codes were added as I went through the data. At the end of the coding process, I reviewed the coded data and either re-classified quotes, or classified them to additional codes as necessary.
4	Develop and review themes	I categorized the codes into higher-level themes that were chosen based on the causal experience being discussed (e.g. economic incentives, technological opportunities), and reviewed them while considering how they might contribute an answer to the initial research questions.
5	Reflect and generate conclusions	I shared my codes and thematic categorizations with my co-authors, and we developed policy-relevant conclusions together. I then extracted the data that supported these conclusions to use in the text of the article. I also investigated whether other data within my transcripts conflicted with these conclusions, and included these instances in my discussion with social or political context to offer further causal explanation.

3.7 Ethics

3.7.1 Positionality statement

Positionality describes the relationship of a researcher to the socio-political context of their research (Coghlan and Brydon-Miller 2014). Positionality statements sometimes describe a researcher as being either an insider or outsider relative to their research subjects (Herr and L.Anderson 2005). However, identity—and thereby positionality—is multidimensional. Rather than considering positionality according to this insider/outsider binary, I reflect on how the dimensions of my identity are situated relative to the subjects of my research, particularly with regards to the qualitative components of my research.

As a white American woman in my early 30s studying at an elite institution, I recognize that my social background has shaped my perspective on and interactions with my subject matter. My understanding of agricultural policy, for example, has been influenced by my experiences working at the World Resources Institute as a land use modeler, where I have had limited experience on working farms. Furthermore, interactions with stakeholders during my interviews may be influenced by my affiliation not only with the University of Oxford, but also with Hilton Food Group (see Chapter 3.7.3). These affiliations could result in the perception that I represent certain institutional interests, which I mitigated by earnestly discussing my feelings regarding who I work with. Conversely, my gender and relative youth may affect power dynamics in a field in which stakeholders are predominantly older males. Lastly, I have been vegan for over 10 years. When it came up in conversation during the interviews, which it frequently did given the subject matter, or because interviewees would offer me food or drinks when visiting their office, I discussed it openly. While it was confusing to many that a vegan is funded by a meat processor, this stark contrast sparked interesting and insightful conversations during the interviews.

As a result of these considerations, I have approached qualitative study design and analysis with reflexivity by recursively examining how the various facets of my identity and institutional positioning might have influenced which voices are heard, and how my preconceived assumptions might shape my findings. This self-awareness throughout the research process has resulted in a conscious effort to engage a wide range of stakeholders, rather than those who are more likely to agree with my views.

3.7.2 Research involving human participants

Oxford University's Central University Research Ethics Committee (CUREC) approved this research involving human participants (Reference Number SOGE C1A 24 127). The approved CUREC form is included in Appendix III, along with the participant information sheet provided to each interviewee. The participant information sheet explains the motivations of the study, and includes questions and answers regarding potential risks, data security, and anonymity.

Prior to each interview, the participants signed a consent form that acknowledged that their data will be anonymized and that they will be referred to in the article by their nationality and stakeholder group (e.g. Dutch farmer #1). The form also explained that they may withdraw their data up until the interview transcript is anonymized. The interviews were recorded using the transcription feature on Microsoft Teams, which was also made clear at the start. At the end of each interview, I explained that a publication draft would be shared prior to submission, and they would have a two-week period to provide feedback to ensure their quotes were sufficiently anonymized.

Although the data were anonymized, I am not publishing the full transcripts as participant identities could hypothetically be determined using references to publicly available information such as descriptions of their job or other affiliations.

3.7.3 Funding

This research is fully funded by Hilton Food Group (HFG), a major UK-based meat processing and packaging corporation. HFG approached Oxford Net Zero (ONZ) for advice about setting net zero targets for their Scope 3 land sector emissions. I worked with my supervisors and the company to modify my original DPhil proposal such that the outputs would be useful to HFG. While this research does not prescribe which metrics companies should use, I aim to inform how companies (specifically Hilton) might measure and mitigate their impact when they consider a broader range of goals and targets than conventional CO_2-equivalent emissions. Furthermore, HFG does not have the ability to influence the outcomes or communication of my research, nor are they co-authors on any of my publications.

Chapter 4: The utility of novel environmental impact metrics in UK ruminant mitigation

This chapter uses quantitative scenario analysis to explore the implications of metric choice for mitigation incentives in the UK livestock sector. The supplementary materials can be found in Appendix I.

The utility of novel environmental impact metrics in UK ruminant mitigation

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Abstract

Much of the UK land sector's environmental impact comes from the production of beef and dairy. Conventional metrics, which understate both the impact of methane reductions and the carbon opportunity cost of land, attribute most of this impact to enteric methane and land-use change from imported soy for feed. Recent developments in agricultural impact metrics necessitate investigation into whether continued reliance on conventional metrics could undermine national (and global) progress on climate and deforestation targets. This article estimates emissions and land use impacts associated with cattle in the UK and applies various combinations of metrics under four futures simulating a range of technological and policy levers. We find that the use of alternative metrics can highlight the potential impact of interventions that might have been overlooked when using conventional metrics, particularly encouraging more efficient production by including the carbon cost of foregone sequestration. We suggest that a range of metrics should be considered to ensure mitigation strategies that deliver on global outcomes, and show that estimates of absolute sectoral impact are acutely sensitive to methodological choices in how it is measured. We also find that the rank-ordering of different intervention strategies for the UK is largely insensitive to metric choice, though this may not be the case for all agricultural systems.

4.1 Main text

Globally, agriculture accounts for nearly a third of greenhouse gas (GHG) emissions (Xu et al. 2021)[1], and uses about half of the world's vegetated land (Ellis et al. 2010). 75% of this agricultural land area is dedicated to rearing livestock, either as pastureland or to grow feed crops (Ramankutty et al. 2008). Much of these climate and land use impacts can be attributed to cattle-rearing for beef and dairy products (Searchinger et al. 2019). As scientists and policymakers explore possible pathways to mitigate these impacts at the country-level (CCC 2020), there has been debate pertaining to how they should be measured, namely with regards to methane and land use. This debate has been particularly active in the UK in recent years, with farmer interest groups advocating for alternative methods of accounting for the impact of methane, and claiming to have one of the most efficient livestock systems (NFU 2021; AHDB 2023a). According to UK national statistics, agricultural production accounts for just over 10% of national emissions (BEIS 2023) and uses 69% of the country's land area (BEIS 2022). A large proportion of these impacts comes from the production of beef and dairy (National Food Strategy 2021; Poore and Nemecek 2018; Brown et al. 2021). This paper will use the UK cattle system as a case study to explore the discourse around metrics used to quantify GHG emissions and land use and will assess the implications of applying each metric in a variety of mitigation scenarios representing hypothetical policy and technology interventions.

The objective of this analysis is to shed light on the role that metric choice could play in the development of national mitigation strategies in the livestock sector, and how those choices could hinder or facilitate progress on global environmental objectives.

[1] Calculated using Global Warming Potential over a 100-year time horizon.

4.1.1 GHG metrics

The production of animal-based products results in emissions of carbon dioxide, nitrous oxide, and methane. The sources of these production emissions (PEMs) include the production and application of nitrogen fertilizers, energy use, manure management, and enteric fermentation (IPCC 2003). Methane, unlike nitrous oxide and carbon dioxide, is a relatively short-lived climate pollutant. Long-lived GHGs accumulate in the atmosphere, while methane breaks down after about 12 years (Allen 2015). This property can be overlooked by conventional GHG metrics.

The Global Warming Potential (GWP) metric is calculated as the relative radiative forcing caused by a pulse emission of a non-CO_2 GHG relative to that due to a pulse of CO_2 over a given time horizon (IPCC 2007; Lashof and Ahuja 1990). GWP calculated over a 100-year time horizon (GWP_{100}) is the most common metric at both the corporate and national levels (WBCSD and WRI 2004; IPCC 2019). Methane is a very strong climate-forcer over a decadal time horizon. Thus, some argue that equating it with carbon dioxide over 100 years underestimates the consequence of increasing—and the benefit of decreasing— methane emissions (Allen, Friedlingstein, et al. 2022; Ocko et al. 2017). GWP is sometimes also reported over a 20-year time horizon, though critics claim this over-incentivizes methane reductions and would allow entities to avoid reduction of CO_2, which accumulates over time (Schaffer et al. 2017).

While GWP (specifically over 100 years) has been widely used, it has also faced criticism. Some have argued that climate objectives can be more optimally met by tracking each greenhouse gas' contribution to radiative forcing over time, rather than trying to use a common unit over an arbitrary time horizon (Sarofim and Giordano 2018; Manne and Richels 2006). Others argue that radiative forcing is less relevant for policy than other outcomes such as temperature change or loss and damage (Sarofim and Giordano 2018; Keith P. Shine et al. 2005). More recent developments in emissions metrics bring attention to the problems that arise when comparing long- and short-lived GHGs.

First published in 2016, GWP* (GWP- star) compares emissions of different greenhouse gases in terms of CO_2-warming-equivalent emissions, recognizing the difference in how cumulative and non-cumulative GHGs behave in the atmosphere (Cain et al. 2019; Lynch et al. 2020; Allen et al. 2018). Rather than equating the impacts of short-lived GHGs to those of CO_2 for a given parameter over a chosen time-horizon, the calculation for GWP* is based on the rate of change of short-lived GHGs over a 20-year period (M. A. Smith et al. 2021). Thus, at least 20 years of historical methane data, or some estimate of what methane emissions were 20 years ago, are required for the calculation. This rate of change mechanism distinguishes it from metrics such as conventional GWP. Using this approach, the results reflect the effect of long-term contribution to warming of changes in annual rates of methane emissions (Allen, Peters, et al. 2022).

GWP* also has limitations. Critics argue that the dependence of the GWP* calculation on recent emissions is advantageous for developed countries where increases in methane emissions occurred in the past, while disadvantageous for developing countries (Meinshausen and Nicholls 2022; Rogelj and Schleussner 2019). Whether constant methane emissions or zero methane emissions are considered the counterfactual heavily influences the perceived impact of current methane emissions (Donnison and Murphy-Bokern 2023; Cain et al. 2021), but does not affect the perceived impact of a permanent change in methane emissions, such as what could be induced by a policy intervention. For example, metrics which incorporate the rate-of-change of emissions (sometimes referred to as ‘flow’ metrics) like GWP* can obscure the warming caused by historical increases in methane that occurred more than 20 years ago (Carter and Urbancic

2023; Cusworth et al. 2023). Thus, it has been argued that GWP* does not appropriately incentivize near-term mitigation, although in reality GWP_{100} understates the warming impact of new methane emissions by a factor of 4 to 5 (IPCC 2021c). We can think of the cooling that would have occurred in the absence of the baseline level emissions as a climate cost of maintained methane.

In recent years, several studies have applied GWP* to assess the warming impact of national livestock systems of Global North countries, either looking at historical effects or the impacts of possible mitigation strategies (Correddu et al. 2023; Liu et al. 2021a; McKenna and Banwart 2024). In each case, the selection of a relatively recent baseline leads to favorable results from negligible to moderate mitigation efforts, potentially encouraging the perverse policy incentives described above. In an effort to address this particularity of GWP*, we introduce a new application called GWP*c (in which 'c' represents the annualized cumulative emissions calculated using GWP* following the cessation of mitigation efforts). This application, which is described further in Section I.1 of Appendix I, highlights what happens when we consider the effects of mitigation decisions through the end of the century with regards to the relative perceived near-term benefit (or consequences) of using GWP*.

Meanwhile, others have explored the longer-term implications of methane-focused versus carbon-focused mitigation (Del Prado et al. 2023), and conducted a comparative study of the use of GWP* and GWP_{100} in Life Cycle Assessment (LCA) literature (McAuliffe et al. 2023). The analysis in this paper builds on these studies, particularly McAuliffe et al (2023) who advocate for more holistic consideration of metrics. Specifically, we build on this previous analysis by exploring the implications of metric choice beyond mid-century and incorporating novel land use metrics.

4.1.2 Land use metrics

In addition to GHGs from the production of food and feed products, agriculture is also responsible for GHGs from altering natural ecosystems both in the past and present (Schmidinger and Stehfest 2012; Johnson et al. 2014; Poore and Nemecek 2018). There is an ongoing debate regarding the allocation of these fluxes to land-based products.

The IPCC defines land-use change (LUC) as “a change in land cover and an associated change in carbon stocks” (Watson et al. 2000; R. A. Houghton 1991). Direct Land Use Change (dLUC) is calculated based on the emissions of conversion from one land cover to another, allocated over a “lookback period”, conventionally 20 years (Anderson et al. 2022; WRI and WBCSD 2022a), which parallels the calculation for GHGs under GWP*, resulting in similar characteristics and drawbacks between the two metrics. One estimation of dLUC at the country level, sometimes called statistical land use change (sLUC), uses a tool built by Blonk Consulting group using FAOSTAT data on both land cover and area per crop (Blonk Consultants 2022; BSI 2012). This approach has been used to calculate LUC by recent life-cycle meta-analyses using a statistical method that assigns emissions to crop expansion in countries that are experiencing net agricultural expansion (regardless of whether or not that crop expands into forests or other land cover types) (Poore and Nemecek 2018; Lam et al. 2021).[2]

This practice in LCAs has the effect of treating existing agricultural land as “free.” So long as agriculture is done on existing cropland or pasture, the amount of land required is irrelevant to emissions, thus rendering the efficiency of food production per unit area irrelevant.

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[2] Note that this method cannot be easily used to measure the dLUC of imported animal products unless the feed inputs and pasture yields used in the country of origin are known and are disaggregated for each animal system.

The carbon impact not accounted for by dLUC can be framed as the foregone sequestration or "prevention of regeneration" of natural ecosystems (Doka et al. 2002). As a proxy, LCA methodology includes the concept of "land occupation," which is the difference between the carbon stock of current vegetation and natural vegetation that would occur in the absence of human appropriation of land (Müller-Wenk and Brandão 2010). One paper by Schmidinger and Stehfest (2012) presents a method for estimating the "missed potential carbon sink" if occupied land were to be regenerated over a given time horizon (Schmidinger and Stehfest 2012). This method builds on an earlier calculation of human appropriation of net primary production (Haberl et al. 2007) to then extrapolate the impacts of that appropriation on the climate.

The Carbon Opportunity Cost (COC) builds on these previous land occupation concepts, offering a metric that acknowledges the foregone sequestration created by human-appropriated land use (Searchinger et al. 2008, 2018). According to the concept of COC, as defined in Searchinger et al. 2018, the allocation of land for human uses has climate costs compared with alternatives. Like with all economic costs, the alternative with the highest climate value is the carbon opportunity cost. If land were not used for one activity (whether beef, crops or biofuels), one could continue to use this land to produce food for others. If not thought of in this way, another alternative would be allowing the land to regrow native vegetation and sequester carbon. Searchinger et al. (2018) argues that in a world that still has expanding agricultural land, the higher value use in terms of agricultural productivity can be viewed as avoided land use conversion elsewhere. It can be approximated as the difference between native potential and present-day carbon stocks on all land on Earth used to generate a particular product divided by the total global output of that product (see Section I.1 of Appendix I). When COC is calculated at the farm-level, the result is sensitive to changes in yield. In this analysis, we use the global (or regional) average because of variation in productivity from place to place. The way COC is calculated in this paper (and in Wirsenius et al. (2020)) can be thought of as the carbon 'benefit' of producing food in the UK rather than anywhere else. COC accounts for the relative efficiency of UK crop production because, if land were taken out of production where yields are higher, more land would be needed elsewhere on average to make up for lost production. Thus, we model the benefits of yield gains in that COC can be reduced as yields improve.

Both Searchinger and Schmidinger apply roughly a 30-year annualization period (approximately equivalent to a 4% discount rate) on the grounds that it aligns with the time horizon selected by policymakers to mitigate climate change (Nordhaus 2017; Searchinger et al. 2018). This reflects a policy judgment that near-term mitigation is more valuable for multiple reasons, including the costs of near-term damages, the extended time that provides for technology and political will to evolve to fully address climate change before crossing tipping points, and the time value of money.

Note that Social Cost of Carbon calculations typically assume lower discount rates, closer to 3% although this use is not strictly analogous for two reasons: it is applied to climate damages rather than emissions and removals, and the COC calculated by Searchinger et al. accounts for the fact that emissions from land use change do not all occur in the first year.

The metrics therefore are conceptually quite different. Both GWP_{100} and COCs reflect the climate costs of pulse emissions. However, GWP_{100} focuses only on effects over 100 years while COCs allocate greater value to effects over a shorter time frame. By contrast, GWP* measures the effect on indefinite long-term warming of permanent changes in methane emissions. One implication of these differences is that GWP_{100} and COCs each have utility to individuals or companies in that they measure the effect of emissions or the use of land independent of the actions of others. By contrast, GWP* is mainly useful as a metric for measuring a permanent *global* change in methane emissions.

The widely-used GWP_{100} metric implicitly adopts a 40-year timescale, since this is the time over which a tonne of CO_2 has the same warming impact as one tonne CO_2-equivalent of methane, and hence the value of GWP_{100} is similar to the adoption of a 3% discount rate (Sarofim and Giordano 2018; Mallapragada and Mignone 2020; Allen et al. 2016). For consistency with previous studies, here we use a 4% discount rate for the calculation of COC, and use GWP_{100}, noting the discrepancy in timescales of interest (30 versus 40 years). Arguments can be made both for adopting a higher discount rate in GWP calculations (for example, the GWP_{20} measure, for which some have advocated to be reported alongside GWP_{100} (Ocko et al. 2017; IGSD 2024), is equivalent to a 7% discount rate), or a lower discount rate in COC calculations.

Given that we understand how these metrics work mathematically, and the functions they serve scientifically, the analysis explores the extent to which the choice of one metric versus another matters for mitigation incentives in the context of UK cattle production. If metrics and mitigation outcomes are misaligned, we risk missing global climate targets and weakening food security.

4.2 UK cattle emissions baseline and mitigation scenarios

National emissions accounting only includes emissions that occur within national boundaries and does not include the impacts of producing inputs to agricultural systems such as synthetic fertilizers or feeds. On the other hand, a product LCA might include both upstream and downstream emissions from the supply chain (de Vries et al. 2015). The analysis presented in this paper does not include production emissions that occur downstream of the farm such as transport or waste management. However, we do include upstream impacts such as the production of synthetic fertilizers or animal feeds because land managers can make decisions regarding which products to purchase as well as quantities. This method is aligned with an 'operational control' approach (WRI and WBCSD 2011), which includes the emissions categories over which land managers have agency at the point of the farm. Although the inclusion of these impacts outside national boundaries goes beyond the requirements of legal targets set by the UK government, including them shows how decisions on farms can contribute to progress on global climate and land use outcomes, which may differ from strategies incentivized by conventional national emissions accounting.

We use several datasets described in the Methods to calculate a baseline for the year 2019 for UK beef and dairy production emissions and land use, shown in Figure 4. 1. The baseline numbers are disaggregated by greenhouse gas to the greatest extent possible. The calculations for the categories included in the IPCC Agriculture, Forestry, and Other Land Uses (AFOLU) guidance are aligned with the results of the UK National Inventory Report (Brown et al. 2021). Domestic COC dominates the baseline due to the relatively large land area within the UK dedicated to grazing.

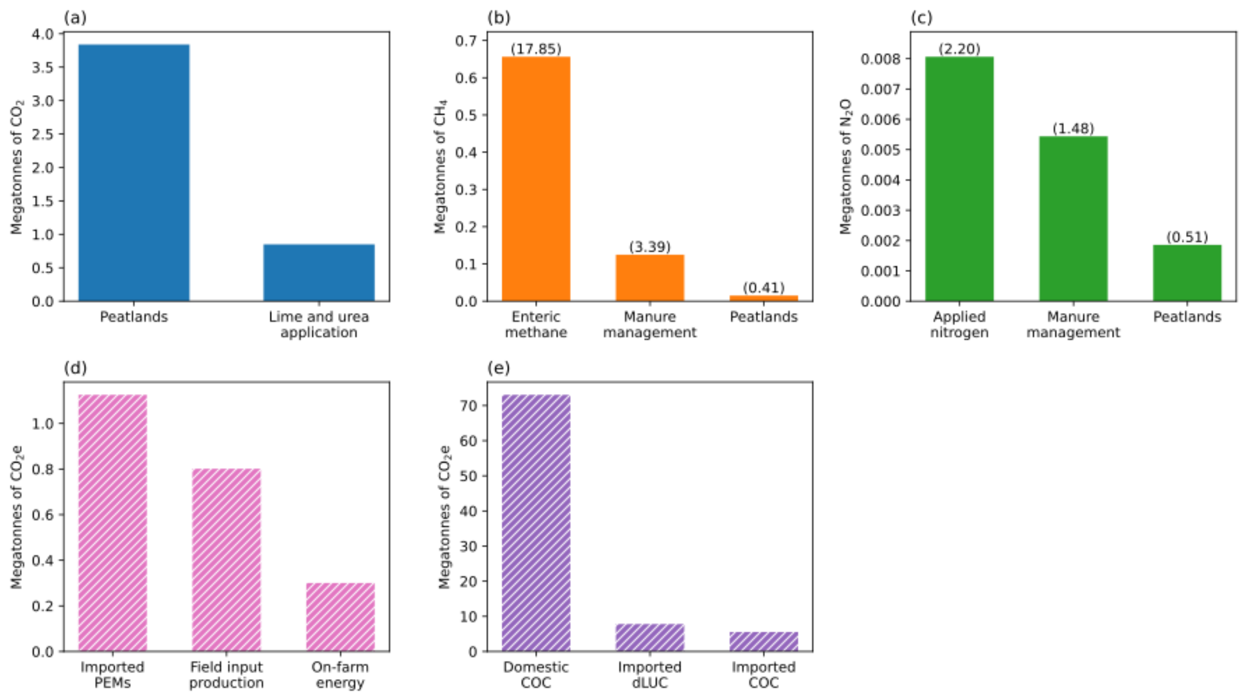

Figure 4. 1 UK beef and dairy production emissions (a-c) and land use emissions (d-e) by source and greenhouse gas in 2019 (baseline). In (b) and (c), the numbers in brackets represent the emissions in Mt of CO_2-equivalent emissions using GWP_{100} to show the scale relative to the other categories. The relative contribution of the carbon cost of land use and land use change compared to agricultural production emissions is more than an order of magnitude larger. CO_2e emissions (bottom center and bottom left) denote categories that could not be further disaggregated by greenhouse gas. Hatched categories are not included in the IPCC's Agriculture, Forestry and Other Land Uses Emissions Accounting Guidance and are thus not included in the UK's national targets, but are considered important under the operational control approach utilized here. The additional categories included were chosen based on those used in Searchinger et al. 2021.

These emissions are then projected to 2050 under four different scenarios described in Table 4. 1. These scenarios are not taken from national or corporate policy, but rather represent varying levels of ambition and different points of intervention to assess how they would affect emissions profiles using different combinations of metrics. This is a bounding exercise, where the real outcome is likely to be somewhere between the extremes, with the middle scenarios serving to explore the mitigation potential of different levers. By being transparent in our assumptions, we can use these scenarios to assess the consequences of doing nothing and the potential benefits of doing everything under combinations of metrics.

Table 4. 1 UK cattle production emissions between 2019 to 2050 are analyzed using projections based on the assumptions outlined in the table. In all scenarios, an increase in production of 25% is assumed to account for projected increases in food demand between 2019 and 2050 in all four scenarios. The percent changes in emissions and land use for all scenarios, and yield gains for the INT scenario can be found in the Supplementary Materials in Appendix I (Table I.2-5)

Scenario	Production Emissions	Land Use Costs
Business As Usual (BAU)	Emissions from agriculture are not mitigated	Yields and feeds do not change
Intensification (INT)	Emissions reductions from improved Feed Conversion Efficiency (FCE)	Feed requirements decrease due to improved FCE, plus yields improve at an ambitious rate
All Existing Technologies (AET)	Mitigation technologies that already exist (though may be nascent) are scaled up to achieve moderate emissions reductions	Feed improvements and yield gains are the same as INT
Breakthrough Technologies (BRT)	New, highly ambitious methods of emissions mitigation are developed by 2050 and are implemented at scale	Assume additional 25% reduction of land use costs due to further yield gains and FCE improvements on top of INT

4.3 Effects of using alternative land use and greenhouse gas metrics

For more ambitious scenarios, the choice of greenhouse gas metric considerably changes the perceived magnitude of mitigation potential for a given intervention, whereas the influence of the land cost metric used is considerable regardless of mitigation ambition (Figure 4. 2). When we consider the long-term implications of using GWP* for each of the four scenarios, using an annualized version of cumulative emissions from 2050-2100 noted as GWP*c, we show that the negative contribution to warming (or cooling effect) caused by methane reductions using GWP* in more ambitious scenarios is short-lived. If the agreed-upon national policy objective is to minimize contribution to long-term future warming, this finding can be applied to inform the timing and level of ambition of methane mitigation required to make progress towards that goal.

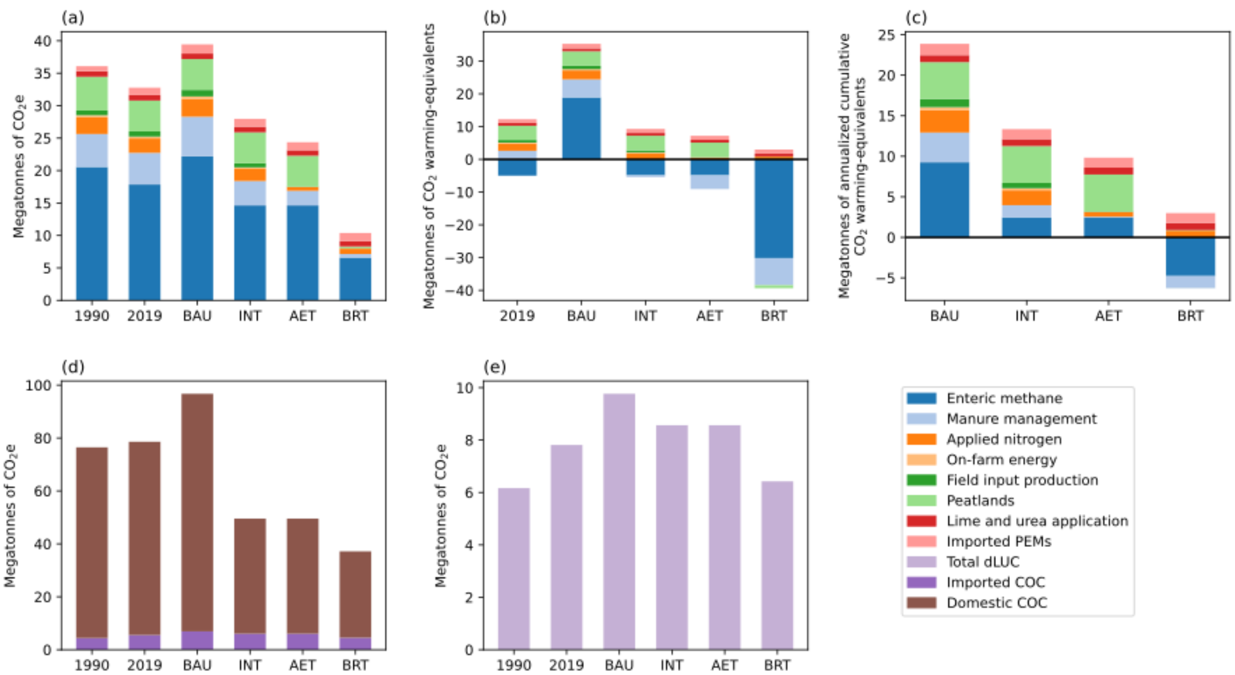

Figure 4. 2 From top left, plots show emissions from UK cattle production calculated using GWP_{100} (a), GWP (b) and GWP*c (c) for the earliest possible historical base year and four 2050 futures disaggregated by emission source. These four scenarios are business as usual (BAU), intensification (INT), all existing technologies (AET) and breakthrough (BRT). GWP*c represents the annualized cumulative emissions from 2050 to 2100 to demonstrate the long-term implications of near-term interventions. The inclusion of this novel application of GWP* demonstrates that the benefits of decreased (or consequences of increased) methane emissions pre-2050 are temporary in order to holistically account for end-of-century effects. The bottom row represents the land use costs of UK cattle production calculated using COC (d) and dLUC (e) for historical base years and future scenarios. Note the relative scale of land use costs relative to GHG emissions, as well as the degree to which more efficient production is rewarded when COC is included. This occurs because COC includes the cost of using domestic land in addition to offshored land use. Additionally, there is no domestic dLUC because the UK has seen no (or very little) native ecosystem loss in between 1990 and present.*

From these results, we also see that the greatest percent reduction between scenarios comes from improved production efficiency (particularly when COC is included in the baseline). The difference between the INT and AET scenarios for any metric is marginal, suggesting that the choice of GHG metric becomes less important in scenarios of moderate mitigation ambition. Between these two scenarios, land use efficiency remains constant. We also do not assume that any land is ‘made free’ to be taken out of production as is often the case in ‘land sparing’ scenarios. Rather, we show the effects of improved efficiency through the application of the COC metric. Though it's true that some interventions that reduce production emissions will also improve land use efficiency, the latter impact would not be reflected by conventional metrics that do not incorporate COCs in scenarios such as these where UK agricultural land use remains constant and there is no conversion to other land cover types such as forestry. In other words, the land savings show up only with COC as an emissions reduction.

With the prevalence of ‘net-zero’ strategies across multiple sectors and at jurisdictional scales (Lang et al. 2023; Net Zero Tracker 2023), we must consider the efficacy of a mitigation strategy to the extent that the strategy is aligned with global climate targets. Some have made the argument that, because the goal of the Paris Agreement is to “pursue efforts” to avoid 1.5°C of warming, policies should focus on managing the contributions of emissions to end-of-century warming (Allen, Friedlingstein, et al. 2022), assuming no further warming thereafter. Alternatively, the target of the Paris Agreement could be framed in terms of keeping peak warming “well below 2°C”. To understand the role that cattle mitigation could play in meeting these targets, we evaluate the impact of cumulative emissions from cattle production on future temperature.

The left axis of Figure 4. 3 shows cumulative emissions to 2100 (assuming no further mitigation after 2050) calculated with each combination of land and emissions metrics, as well as the emissions metrics without land costs. The right axis shows the contribution to warming in degrees Celsius calculated using the Finite-amplitude Impulse Response (FaIR) model for emissions with and without each land metric.

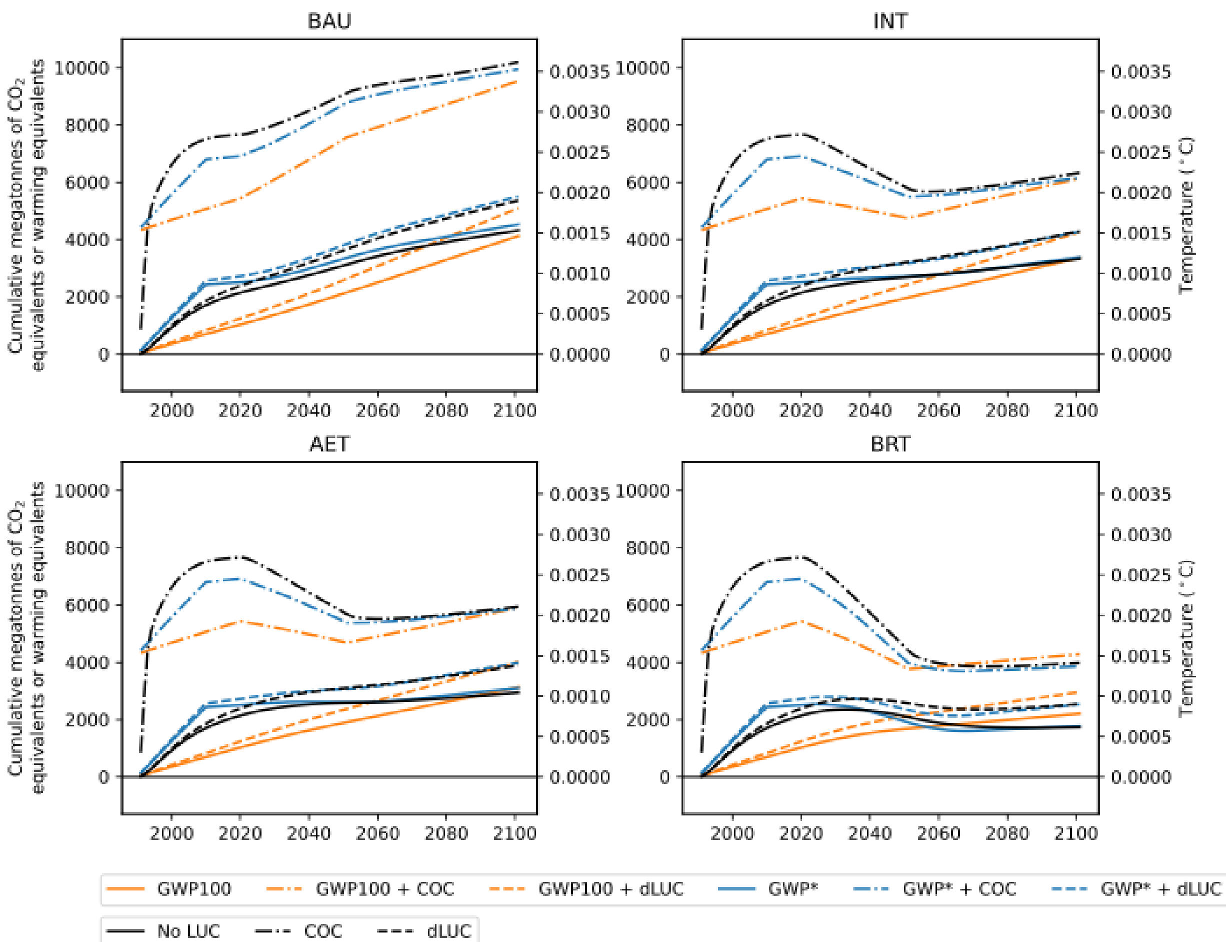

Figure 4. 3 Left axis shows cumulative emissions from cattle production (Mt) of all greenhouse gases from 1990 to 2100 for the four scenarios under GWP (blue) and GWP_{100} (orange), with COC (dot-dash), dLUC (dash) and without any land use metric (solid). The right axis shows additional warming relative to 1990 with each land use metric and without, shown in black. The solid black line shows warming without land use, black dashed shows warming with dLUC, and black dot-dashed shows warming with COC. The figure shows that, on a centennial timescale, cumulative emissions measured using GWP* are more closely aligned with the trend of those emissions' impact on temperature. Note that GWP_{100} (CO_2-e) and GWP* (CO_2-we) are measuring two different things which, some have argued, brings up an issue of whether the two can reasonably be included in the same figure or calculation* (Del Prado et al. 2023). *We address this discrepancy with the distinction of units on the y-axis, and show the results in this way because comparison of the two metrics happens, whether warranted or not. Through our analysis we discuss the limitations of doing so.*

We point out that the sharp increase in the first 20 years using warming-equivalent emissions (blue) is due to our decision to neglect pre-1990 emissions. GWP* requires a choice to be made around the base-year, and additionally pre-1990 data were limited. Nevertheless, the explicit focus here is on the warming impact of methane emissions after 1990: including the impact of pre-1990 emissions would change the height of the curves, but would not significantly change their shape from 2010 onwards, and hence does not affect the relative long-term impact of different policy interventions. This is an important general point about the use of warming-equivalent emissions: decisions on the choice of reference year to begin calculations of warming may affect the stated absolute impact of a sector or activity, but the treatment of emissions more than a few decades ago do not affect the estimated impact of decisions made from this date forwards. Regardless, the shapes of the contribution to warming lines generally follow the shape of the GWP* emissions profiles. By the end of the century, cumulative emissions under GWP* and GWP_{100} approximately converge because of the choice of 100-year time-horizon (Allen et al. 2021). However, if the priority is to achieve the lowest possible peak temperature between now and 2100, the effect of emissions on temperature between now and the end of the century is critical.

Additionally, to include COC in Figure 4. 3, we must de-amortize the emissions factors, and the emissions from COC must not accumulate. This is necessary because COCs do not represent a flux of GHGs going into the atmosphere year-on-year. Rather, they can be conceptualized as a one-off emission occurring in the base year (1990). For each year thereafter, the accumulated value is simply the difference in COC for that year relative to the previous year. In this sense, we capture the idea that decreasing land use represents a decrease in emissions while an increase in demand for land is thought of as an increase in emissions. For this reason, the lines including COC in Figure 4. 3 start at a non-zero value in 1990.

Figure 4. 3 shows that, while GWP* more closely aligns with the modeled temperature impact in the near-to-midterm, the GWP* and GWP_{100} lines tend to converge by the end of the century. This is the case in all scenarios except the Breakthrough (BRT) scenario in which there is a

slightly more noticeable discrepancy (with GWP* more closely mapping to temperature). In all cases, particularly in the near-to-midterm, the shape of emissions under GWP* matches the temperature curves more closely than GWP_{100}. This reaffirms previous findings in the literature around methane that GWP* is useful in understanding warming impacts between now and 2100 to minimize peak warming. This calculation also finds that the difference between metrics matters more in more ambitious mitigation scenarios. Importantly, only in the BRT scenario does contribution to further warming cease in this century.

On the matter of the land metrics, the rank ordering of outcomes is the same in each scenario—COC is always highest, followed by dLUC. The warming impact from COC alone accounts for between 30-50% of the total contribution to warming by the end of the century.

4.4 Discussion

This analysis is a critical assessment of conventional and alternative methods of agricultural emissions accounting and points out important considerations as developed nations with ambitious climate targets decide how to tackle the complex objective that is feeding the world within planetary boundaries. In summary, the relative ambition of various mitigation strategies is heavily influenced by the choice of metrics used to track both greenhouse gases and the carbon costs of using land for agriculture, but the perceived preference for different outcomes is unaffected. Hence, while decisions regarding which greenhouse gas metric to use and whether to consider the carbon opportunity cost of land affect the absolute perceived impact of UK cattle, they do not affect the relative benefits of decisions going forward.

Our results in Figure 4.2b show that the use of GWP* can generate the perception that methane reductions offer a pathway for emissions from cattle production to appear 'net zero by 2050' although meeting the goals of the Paris Agreement at a global scale requires all industries, agriculture included, to sustain no further warming for many decades. The longevity of stabilized warming, however, is dependent on mitigation of long-lived GHGs as demonstrated by the use of GWP*c in Figure 4.2c. We point out that 'net zero' under GWP* can essentially be interpreted as 'no contribution to further warming relative to a baseline.' This is demonstrated in the Breakthrough scenario, in which cooling due to reductions in methane emissions counteract warming from residual long-lived GHGs in the near-term. This is very different to the interpretation of net zero using GWP_{100}, which is not relevant for temperature outcomes, but rather the balance of sources and sinks of GHGs equated to one another based on radiative forcing effects over 100 years.

By focusing attention on the effect of changes in emissions, ongoing cattle production can technically cease to contribute to warming increases at the national level. However, even continued beef and dairy production can hold up temperatures, thus GWP* should not be used to justify leaving methane out of mitigation strategies. Even if global agricultural methane is technically contributing no further warming, this could cause temperatures to stabilize above 2°C, meaning the goals of the Paris Agreement would not be met as a result. Nevertheless, the potential for temporary cooling due to methane abatement can still be considered while simultaneously working towards achieving net zero emissions of long-lived GHGs.

The notion that warming-based metrics provide a potential route to net zero warming for the agricultural industry fuels the misperception that these calculations somehow flatter livestock production (Meinshausen and Nicholls 2022). Indeed, many countries and jurisdictions with high (albeit stable) methane emissions have advocated for the adoption of GWP* on the misunderstanding that it would alleviate the pressure to ambitiously reduce methane, particularly in the livestock sector (Brownlie 2023; B+LNZ 2021; Place et al. 2022; Boren 2022). In fact, the reverse is true: warming-based metrics increase the incentive for near-term methane reductions. To that effect, a response from the scientists behind GWP* to a critique from Rogelj et al. (2019) explains that whether entities should choose to undo warming caused by methane but not CO_2 is a distinct policy issue, the resolution of which is facilitated by GWP* and its use in understanding the effects on temperature of mitigation decisions (Cain et al. 2021).

The long-term effects of using GWP* are demonstrated in Figure 4. 4, which shows the two most extreme scenarios of emissions from UK cattle. In the BAU scenario, methane emissions increase in the absence of mitigative efforts, while the BRT scenario involves ambitious emissions reductions in every category, assuming the rapid development of mitigation technologies that are not readily available today. In the former scenario, emissions measured with GWP* rise more steeply than under GWP_{100} but converge around mid-century, while the latter sees a steeper reduction and a greater divergence from GWP_{100} at mid-century. Conversely, the end-of-century differential is greater in the BAU case in comparison to BRT. This suggests that metric choice under ambitious mitigation is more important in the near-term. However, as we find in Figure 4. 3, the end-of-century warming impact is largely determined by the choice of land use metric, meaning the choice of GHG metric is less important in the long-term.

In Figure 4. 3, we set all pre-1990 emissions to zero and explain why this is necessary to be able to compare cumulative emissions to warming. We do not make the same assumption in the calculation for Figure 4. 4 because doing so would result in a sharp increase in emissions from 1990 to 2010, which would distract from the purpose of the figure. The purpose of Figure 4. 4 is to show ongoing rates of emissions, which are more relevant to and, in the case of CO_2-we emissions, proportional to contributions to the ongoing rate of warming. Hence, we here calculate GWP* emissions using historical emissions up to 1990 because we are not focusing on the cumulative impact of emissions since then. The difference between Figure 4. 3 and Figure 4. 4 illustrates the impact of decisions regarding the treatment of historical emissions on the absolute level of ongoing emissions, as well as how it does not affect the predicted impact of decisions going forward.

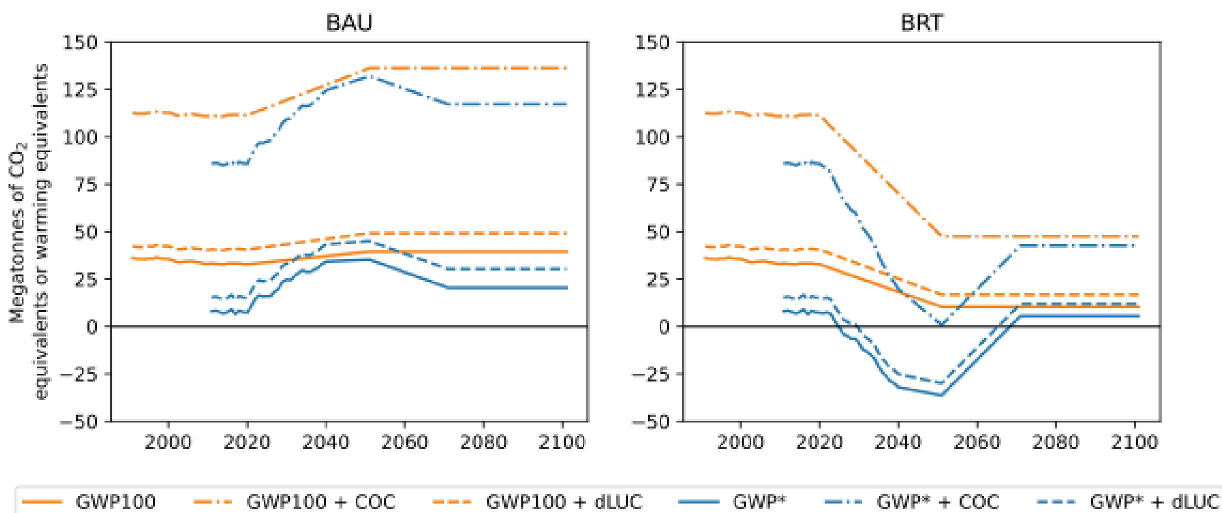

Figure 4. 4 Historical and projected emissions attributable to UK cattle production under GWP_{100} (orange) and GWP (blue), considering methane alone (solid), including impact on CO_2 using dLUC (dashed), and COC (dot-dashed) for the BAU (left) and BRT (right) scenarios. The GWP* lines show the long-term implications of interpreting penalties and benefits due to changes in methane. The inclusion of COC makes baseline emissions significantly higher, but highlights opportunities for greater reductions through improved production efficiency in the BRT scenario.*

The inclusion of land use emissions metrics in the scope of assessment can offer new points of intervention that might not otherwise have been pursued. For example, improving the efficiency of land use through intensification and improved feed conversion efficiency has the highest relative mitigation potential, particularly when using COC. Unlike other 'land sparing' modeling, we do not assume that intensification in one place leads to native vegetation in that same country. The calculation of COC assumes that it is not possible to say where the land sparing would occur. It is therefore more apt to say that producing more food in one place avoids conversion of native ecosystems elsewhere. We also do not assume that any land is taken out of production.

The most impactful option for mitigating dLUC is to stop buying feeds such as soy from areas of high deforestation, although this intervention would have no effect when using COC because COC is origin-agnostic. In theory, dLUC disincentivizes sourcing of products linked to recent deforestation such as soy and cocoa (WRI and WBCSD 2022a). In practice, as data at the country level is most common, dLUC incentivizes shifting supply of such commodities from the Global South to the Global North where deforestation happened long ago (R. Taylor and Streck 2018). As a result, leakage becomes extremely likely when dLUC is reported at the sub-global level so long as demand remains constant. Thus, we reaffirm that major opportunities to incentivize progress on global land and climate targets are being undervalued or disregarded due to this convention in livestock impact assessment. Section I.2 of Appendix I contains further analysis around the mitigation potential of soy sourcing using COC and dLUC.

This analysis is a bounding exercise that uses hypothetical mitigation scenarios to model different levels of ambition. Because the scenarios do not attempt to predict future conditions in a robust way, results are not prescriptive, but rather illustrative. Additionally, we highlight gaps in the data required to model UK livestock emissions. We find that reliable information on the quantities and types of feed used specifically for cattle were particularly lacking, thus the impact of feed production has substantial uncertainty. Due to these data gaps, our analysis relies on certain assumptions, many of which are crude, though we identified the most significant uncertainties and tested them with sensitivity analyses. These assumptions are discussed in the Methods.

There are mathematical symmetries between these metrics that must be acknowledged. Both GWP* and dLUC are calculated using a 20-year lookback period. Thus, GWP*, like dLUC, can also lead to leakage when reported at the sub-global level.

There is a second symmetry to consider between COC and GWP*, particularly when they are thought of as cumulative over time. Both metrics allow for the consideration of 'opportunity costs' as a mitigation strategy. As previously discussed, COC is the opportunity cost of using land for one purpose as opposed to another. Similarly, constant rates of methane emissions represent an opportunity cost in that they 'hold up' temperatures relative to a world in which those emissions are absent. For this reason, we must look at the rate of change from one year to the next (COC), or over 20 years (GWP*) to more appropriately represent the effects of interventions using these metrics over time.

While COC and GWP_{100} can incentivize certain actions without the need for global reporting, they also have shortcomings. COC has been criticized because it represents avoided sequestration rather than an annual carbon flux. It therefore does not reflect additional emissions or removals, which are the focus of national inventory reporting. GWP_{100} has also been shown to be equivalent to a "social cost of emissions" with a specified discount rate (Azar et al. 2023). Both metrics have been criticized due to the dependence of the results on the selected time horizon.

There are two important conclusions to be drawn from this analysis. First, in the case of UK ruminant mitigation, the rank-ordering of mitigation performance of policy options is insensitive to the choice of emission or land-use metric, which primarily only affect the perceived absolute level of harm caused by the cattle industry. Hence the impact of metric choice on actual, forward-looking decisions may be overstated in ongoing discourse. Note that there may be other contexts, such as where an intervention trades a decrease in nitrous oxide for an increase in methane, where metric choice does affect rank-ordering of mitigation decisions, so a case-by-case consideration of these effects is warranted.

While metric choice does affect assessments of absolute or total harm, these are even more sensitive to other arbitrary choices that are often overlooked, such as the choice of initial year from which to evaluate historical responsibility. Note that this is only the case because we assume a given rate of production in this analysis. The perceived benefits of reducing production are acutely sensitive to metric choice: with dLUC, reducing production is always beneficial, with COC, reducing production is only beneficial if land-use in a region is less productive than the global average. This point is especially relevant in the current policy landscape where the feasibility of many climate strategies for the land sector (including that of the UK Climate Change Committee) depend almost entirely on ‘freeing-up’ land by reducing agricultural production and assuming a change in national diets. Whether or not this is a plausible future and thus a reasonable assumption remains a critical question that warrants further investigation.

Second, the only scenario that results in the UK cattle sector ending its contribution to ongoing warming (BRT) involves mitigation with a level of ambition that is not currently technologically possible without reducing the UK’s share of global meat production. Whether or not reducing production would be a good thing for the global environment depends on current and near-term trends in UK farming efficiency relative to competitors, and on global dietary trends.

We reiterate that land use and climate impacts beyond the national boundary are not included in conventional national emissions accounts. Given the scale of these impacts, regardless of metric chosen, and that conventional accounting leaves open the option to meet national climate targets by offshoring agriculture elsewhere, this analysis highlights how points of intervention are affected by changes to spatial and temporal boundaries.

Impact on temperature aside, producing more food on less land is important for preserving and restoring global biodiversity, food security, and other valued outcomes within the food system. Thus, policymakers should consider setting targets based on a desired outcome; if the priority is minimizing global pressure to convert land, COC is the most helpful metric. If the objective is to minimize supply-chain emissions associated with deforestation, dLUC is potentially more informative, but creates perverse incentives such as potentially diverting feedstock supplies to countries that have less stringent LUC targets. If the aim is to minimize contributions to warming, GWP* is more informative than GWP_{100}, but is sensitive to historical data and hence opens contestable issues about responsibility. Ultimately, if conventional metrics are not creating sufficient incentive to drive progress towards global targets around climate and land use, we suggest an alternative approach. Therefore, we cannot rely on convention, nor can we rely on a single number to achieve multiple complex outcomes. Holistic consideration of a wider range of land use and GHG metrics, while recognizing their limitations, could help lead the land sector to remain within multiple planetary boundaries.

4.5 Methods

This analysis uses data exclusively for cattle in the UK. For LCA accounting purposes, cattle are either categorized as calves, heifers, dairy cows, bulls, or beef cattle. LCA literature typically distinguishes a beef herd and a dairy herd depending on the product coming from the herd (though note that about 50% of the UK's beef output comes from cattle that originate in the dairy herd (Clarke 2024)). The UK National Inventory Report (NIR) only provides a population breakdown into dairy and non-dairy rather than the five categories listed. Additionally, individual cattle can shift between dairy and beef herds, making the allocation of impacts even more complex in the context of this analysis. According to a DEFRA dataset on herd populations, dairy cows are defined as milk-producing female cows in the dairy herd over the age of 2 years (DEFRA 2023c). Cows that are producing milk consume more feed and emit more enteric methane per head than other populations, thus it is reasonable to break apart the national herd in this way to model them separately. For this reason, it is difficult to model non-milk-producing cattle in the dairy herd (i.e. heifers and calves) separately from the beef herd. Thus, our calculations were done in terms of 'dairy-producing' and 'non-dairy producing' as this better represents the disaggregation of data available in the NIR, as opposed to separately modeling the dairy and beef herds.

The calculations in this paper used a modified version of the Excel model created for an analysis of mitigation opportunities for the Danish land sector (Searchinger et al. 2021).

4.5.1 Production emissions

This analysis used several datasets, primarily the UK NIR and feed data from DEFRA (DEFRA 2022). Because the NIR data for 2021 were not yet finalized at the time of analysis and we take a

3-year average, we used a base year of 2019 with the average taken from 2018 to 2020 to account for annual fluctuations. All production emissions are disaggregated by greenhouse gas whenever possible, which is necessary to apply different metrics. However, some sources were only available in CO_2-equivalent units (GWP_{100}) and cannot be disaggregated by greenhouse gas. This is not a major source of error because, for the categories where emissions cannot be disaggregated (on-farm fuel use, nutrient input and pesticide production, COC, and dLUC), the dominant GHGs are carbon dioxide and nitrous oxide. This would therefore not affect the outcome if GWP* were applied, which would only be influenced by fluxes in methane. The emissions categories from the Agriculture section of the NIR that distinguish between emissions from cattle and other animals are limited to enteric methane and manure management (methane and nitrous oxide).

Drained peatland emissions are reported in the NIR (Annex Section 3.4) broken down into CO_2, N_2O, and CH_4 per hectare per year along with the total drained area. Applied nitrogen (organic, synthetic, and crop residue) emissions only involve N_2O, and are also reported in the NIR. The rates of nitrogen application for each crop can be found in Table I.6 of Appendix I. However, on-farm energy use is available in CO_2-equivalents. To estimate emissions from on-farm energy, we used another DEFRA dataset (DEFRA 2013), which provides an amount of diesel used per hectare of cropland. We then used a conversion factor from FAOSTAT to convert liters of diesel to CO_2e. This value could not be further disaggregated. We also estimated barn energy consumption. In a 2021 analysis of the Danish livestock sector, we estimated 0.1 GJ electricity per dairy cow slaughtered per year (Searchinger et al. 2021). In the absence of any more relevant data, we use this figure with the understanding that it is likely an overestimation because most livestock in the UK graze on pasture, whereas Danish dairy cattle live mostly in barns, which are more energy intensive.

Other than for enteric methane and manure management, data is only available at the national level rather than by product or livestock type, and thus requires some reasonable method for allocating an amount to cattle. Most other production emissions categories (applied nitrogen, lime and urea, and pesticide and fertilizer use) are dependent on the area required to produce the feed or roughage for beef and dairy production. However, data were not readily available on the breakdown of each feed type by animal. Instead, a dataset from the Agriculture and Horticulture Development Board (AHDB) provided the quantity of feed by crop (i.e. wheat, barley, etc.) and a second dataset from the same source reported total feed quantity by animal type (i.e. cows, sheep, etc.) (AHDB 2022). According to the latter dataset, cattle consume 37% of feed in the UK, however this figure does not include roughage. Thus, we assumed that 37% of all feeds are used for cattle. This ratio has not materially changed significantly since the early 1990's (at which point it was between 38-40%). This assumption is a likely source of error because not all animals consume feed baskets with the same composition. This assumption allows for the estimation of emissions sources that are not delineated by animal type. For example, we assumed that 37% of lime and urea emissions can be attributed to feed used in cattle production, and that 37% of drained peatland used for cropland is producing crops for cattle. Note, however, that we make separate assumptions for the consumption of grass and forages.

For land dedicated to cattle grazing, we assume that 70% of total grazing land is used for cattle because only cattle and sheep graze on peatland, and cattle consume 70% of digestible feed (including grazing) according to the NIR's supporting data (United Kingdom 2020). This ratio also has not changed since the early 1990's as determined using data from the 1990 to 2019

Common Reporting Format. We apply this ratio to peatland dedicated to grazing. The NIR source used distinguishes the differentiated uses of upland from lowland peat. This is an important consideration because most upland peat is used for grazing while lowland peat is dedicated to horticulture. The disaggregation of the NIR data allows for the consideration of these differences.

All production emissions categories were reported between 1990 and 2019, with projections to 2050 under the mitigation strategies described in Table 1. The UK NIR 1990 to 2019 report provides this back-data for enteric methane, manure management, peatland, and applied nitrogen, which we scaled based on the 2019 value calculated specifically for cattle (Brown et al. 2021). We used the FAOSTAT quantity for fertilizers and pesticides used in 1990, also scaled for cattle based on the 2019 value, then linearly interpolated between 1990 and 2019. Lastly, the NIR provides areas of drained peatland for 1990 and 2019 only, which we also scaled and linearly interpolated (Brown et al. 2021).

Descriptions of each category of emissions can be found in Section I.4 of Appendix I. Additionally, the historical emissions used in our calculations can be found in the Supplementary Materials (Table I.7).

4.5.2 Domestic and imported feed

In addition to production emissions, this study's focus on measuring land use required detailed analysis into the feed allocated to cattle systems. Domestic feed data came from DEFRA, which provided the quantity of each crop that is used as feed (DEFRA 2022). We used a three-year average (2018 to 2020 for a base year of 2019) to minimize effects of fluctuations.

Quantities of imported feed crops that are also produced domestically (i.e. wheat, which is imported and produced domestically) are provided by the same DEFRA dataset used for domestic feed quantities, although it doesn't specify the quantities of imported crops used for feed. We estimated the quantity of imported crops used for feed based on the proportion of domestically produced crops that are used for feed. For example, if 50% of domestic wheat is used for feed (according to DEFRA), we assume 50% of imported wheat is used for feed. For the remaining feed crops that are not produced domestically, we assumed 100% are used for feed. This is likely to be a reasonable assumption because the imported feed crops are not typically used for human consumption (e.g. oilseed cakes).

Domestic feed quantities in the DEFRA feed dataset are available back to the 1980s, so we averaged 1989 to 1991 values to get a base year of 1990, and an average of 2018 to 2020 for a 2019 value (both with 37% scaling factor for cattle). Imported crops also produced domestically are available through the same dataset. However, imported crops not produced domestically are only available back to 1992 through the AHDB dataset. Thus, we used an average from 1992 to 1994 (implied 1993 base year) as a proxy for 1990, and a 2018 to 2020 average for 2019. Domestic and imported feed quantities were then linearly interpolated between 1990 and 2019. The quantities of domestic feeds used in the calculations can be found in Appendix I (Table I.8).

Lastly, we included an estimation of the production emissions from imported feed. These are the emissions from applied nitrogen and lime, farm equipment, transportation, and processing for feed crops produced abroad. Because most feed used in the UK (but not all) comes from Europe, we used the average emissions factor of the European region and the global value, as was done in a 2020 WRI report, which also provides regional emissions factors for Europe (Wirsenius et al. 2020).

4.5.3 Land costs and imported feed production emissions calculations

The back-data from 1990 to 2019 and projections under various mitigation scenarios to 2050 were analyzed using various combinations of land and emissions metrics. The analysis applies combinations of GWP_{100} and GWP* for production emissions and dLUC and COC for land use costs.

The Carbon Opportunity Cost calculations used an average of the Global and European factors used in Wirsenius et al. (2020). These values are currently being updated, though the most recent published values were used in this analysis. The dLUC data comes from an early free version of the Blonk Land Use Change tool (Blonk Consultants 2013), which was used in the 2018 Poore and Nemecek food LCA meta-analysis (Poore and Nemecek 2018). The tool uses a 2010 base year with a 20-year look-back based on when the FAO's Forest Resource Assessment was completed. This data, which has not been recently updated, is used to calculate weighted-average emissions factors for each imported feed based on the quantities of each feed from each origin, and the dLUC factors of each origin. The quantities of feed from each origin come from the FAOSTAT trade matrix (FAOSTAT 2023b). Note that the Blonk data includes emissions factors per hectare for CO_2, N_2O, and CH_4. However, COC cannot easily be disaggregated in the same way. Thus, to maintain consistency across the land metrics, dLUC is also only aggregated as CO_2e using GWP_{100} constants.

In the calculation of cumulative COCs, we apply de-amortized values from the background data of the calculator built for Searchinger et al. 2018. This data gives the global historical native carbon stock lost to date due to the production of a certain crop and the total carbon stock of that crop, globally. These difference between these two values, divided by the global output of that crop, gives us the de-amortized COC that can be counted cumulatively.

Emissions factors for production emissions of imported feed, COCs, and dLUC can be found in Table I.9 of the Supplement. De-amortized COC values are in Table I.10 of the Supplement.

4.5.4 COC for pasture

Because grass and forage consumption is not reported alongside other feedstuffs, we must make a series of plausible assumptions to calculate the land use costs of UK cattle grazing.

According to a report on UK Agriculture from the Scottish Government, the UK dedicates approximately 5.2 million hectares to grazing (Scottish Government 2016). We then apply the previously stated assumption that cattle utilize 70% of the country's grazing land based on the NIR figure that cattle consume 70% of digestible energy out of all ruminants (cattle and sheep) to allocate 3.7 Mha to cattle. Based on calculations from a previous comparative study (Wirsenius et al. 2020), the native potential carbon stock for pasture in the UK is 137 tC per hectare, and regional average pasture yields are 6 tC per hectare, resulting in an average carbon loss of 131 tC per hectare. After amortizing this carbon loss over a 30 year period, we get a COC factor of 16 tonnes of CO_2e per hectare of pastureland, or 0.73 tonnes of CO_2e per tonne of grass. The native potential carbon stock is calculated using CAPRI land cover data at 0.5-degree resolution overlaid with the supplementary Global Carbon Loss data from Searchinger et al. (2018).

4.5.5 Mitigation scenarios and production increases

The mitigation scenarios in this analysis are defined by assumed percent changes in each emissions category and feed quantity applied linearly between 2019 and 2050. The percent changes for each emissions category in the Intensification scenario are based on the results of analysis of feed conversion efficiency improvements in Denmark due to a lack of equivalent data in the UK (Wirsenius et al. 2020). The percent reductions in the Existing Technology and Breakthrough scenarios are also based on the analysis from the same paper (which analyzed the potential mitigation of all technologies in one scenario), but here are split into two scenarios of varying levels of ambition.

The results of the analysis also depend on the assumed percent increase in production applied linearly between 2019 and 2050. Projected percent increases vary by product and by region (Searchinger et al. 2019). Previous analysis applies a 45% increase based on global projections (Wirsenius et al. 2020), however this is likely an overestimate for livestock in the UK given that production of beef and dairy has remained approximately stable over the past several decades (FAOSTAT 2023a). However, the market for livestock products is global, and it's possible that if demand grows significantly in other parts of the world (as projections suggest), countries like the UK and other countries in Europe could increase production to meet demand. Thus, we chose a middle-of-the-road value of 25% applied linearly across all four scenarios included in the analysis and conduct a sensitivity for other values, both higher and lower (see Appendix I Section I.5). This increase is applied uniformly across the beef and dairy herds, assuming no changes to production efficiency, which we model separately. We found that the choice of percent increase does not impact the favorability of each metric.

In the scenarios that involve significant yield gains, we do not assume any land is taken out of production. While many models explore the potential for afforestation due to either yield gains or shifting diets (Griscom et al. 2017; Collas and Benton 2023b; Theurl et al. 2020), and indeed this is the implied trajectory in the UK national land sector strategy, we do not include this in our calculation based on historical trends. Since 1990, land area dedicated to agriculture in the UK has not changed. However, meat and dairy production has, on average, stayed fairly constant despite a decline in heads of cattle, implying improvement in yields over that time period (FAOSTAT 2023a). Thus, we assume any yield gains would result in either lower imports or higher exports, as opposed to changes in land cover. We assume any increases in yield gains would go towards meeting global increases in demand for food, thus avoiding the need to clear land elsewhere (Searchinger et al. 2019).

For the sake of these stylized scenarios, we assume that emissions do not change after 2050 as this is in line with most national UK climate scenarios (such as the CCC). This means that, whether emissions are increasing or decreasing pre-2050, emissions level out from 2050 to 2100. Of course, this is unrealistic, but for our purposes of exploring the implications of metric choice particularly regarding methane, it is useful to show what happens when the rate of change of emissions stagnates. To address the result shown in Figure 4.2.c, which suggests that strategically timed abatement of methane measured under GWP* can be used to 'appear' climate-neutral by 2050, we apply GWP*c to demonstrate that these benefits do not last to the end of the century.

GWP*c is the annualization of cumulative emissions from 2050 to 2100, after mitigation (or increases) of emissions has leveled out. Including this calculation shows that cooling is only possible so long as methane emissions are decreasing. In the case of UK cattle, the end-of-century warming impacts are significantly dampened relative to the effect of GWP* in 2050 (See Figure 4.2 (b)).

4.5.6 FaIR climate model

The Finite-amplitude Impulse Response (FaIR) model is a climate model that converts emissions profiles into temperature (contribution to warming) (Leach et al. 2021). The model calculates the contribution to warming of our scenarios by first calculating the temperature impacts of a given shared socioeconomic pathway (SSP, in this case SSP-245), which is a projection of emissions based on a set of assumptions about future mitigation, or lack thereof. Then, the model is run a second time with the emissions of that SSP, less the emissions of the scenario in question (e.g. UK beef under the BAU scenario). Thus, the temperature impact of our scenario is the difference between the results of these two runs. For each of the four mitigation scenarios in this analysis, we calculate contribution to warming for production emissions alone as well as with COC and dLUC included.

While it is valuable to report discounted COC in annual attributional accounts to provide a snapshot of land use each year, conceptual issues arise when incorporating COC into a cumulative emissions profile due to the use of a discount rate. To apply COC in a warming model, we must de-amortize the emissions. COC is not a flux of emissions entering the atmosphere every year as is the case with other sources such as fossil fuel use, enteric methane, etc. Rather, COC can be represented as a pulse of emissions in year 0 equal to the COC in that year, after which the emissions do not accumulate. However, if COC increases, the difference between that year and the previous year is accumulated. Likewise, a reduction in COC (such as through improved efficiency) would be represented as a removal. A table of the de-amortized COC emissions factors can be found in Supplement Table I.10.

Chapter 5: Integrating the carbon opportunity cost into farm subsidy schemes

This chapter presents a new tool to estimate the global impacts of farm-level decisions based on emerging UK farm subsidies that prioritize on-farm biodiversity and carbon storage, proposing how food production can be included as a 'public good' under the umbrella of 'public money for public goods' as it relates to the Post-Brexit farm subsidy scheme, ELMs (Environmental Land Management schemes). The supplementary materials can be found in Appendix II.

Integrating the carbon opportunity cost into farm subsidy schemes

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Abstract

The land sector must reduce greenhouse gas emissions and support ecosystem recovery while maintaining food production under finite land availability. In the UK, recent agricultural subsidy schemes promote interventions including afforestation and agroecological practices aimed at enhancing biodiversity and carbon storage. However, many of these interventions have highly variable effects on agricultural yield. In the absence of diet shifts, lost food production must be replaced elsewhere, potentially leading to land use change emissions that counteract domestic emissions reductions. Here we present the **Farm Productivity Evaluation Tool (FarmPET),** a heuristic farm-level decision-support framework designed to explore the trade-offs between avoided on-farm emissions, carbon sequestration, and the Carbon Opportunity Cost (COC) of foregone food production. The tool applies ranges of yield responses for crop systems, and farm-level data for pasture-based beef systems to illustrate how outcomes depend on both productivity and mitigation potential. On arable land, FarmPET demonstrates that interventions that maintain or improve yields are associated with net climate benefits, while interventions that reduce productivity lead to uncertain outcomes once COCs are considered. For grazing systems, the benefit of afforestation depends jointly on livestock productivity and forest sequestration rates, leading to variable net climate impacts. We find that the net effect of an intervention depends on farm efficiency and yield responses, and that productivity is important in determining whether land use interventions deliver net climate benefits at the global level. By incorporating the

implications of foregone production, we provide a transparent way to examine farm-level trade-offs.

5.1 Introduction

The United Kingdom currently dedicates approximately 70% of its domestic land area to agriculture (DEFRA 2023a). In addition, an area equal to the UK's domestic agricultural land is required overseas to produce food and feed which is then imported to the UK (NFS 2021). Of all the land used to feed the UK, domestic and overseas, 85% is used either for grazing or to produce feed for livestock (de Ruiter et al. 2017). Using carbon dioxide-equivalent emissions over a 100-year time horizon, the Agriculture, Forestry and Other Land Uses (AFOLU) Sector accounts for just over 10% of national emissions (Climate Change Committee 2020; Westaway et al. 2023). UK agriculture is also responsible for a significant amount of biodiversity loss worldwide, with one estimate from the WWF suggesting the extinction of at least 33 species globally can be attributed to the UK's food supply (IPBES 2019; WWF 2017).

The UK's national strategies proposed for mitigating agriculture's undeniably large environmental impact focus primarily on domestic emissions, in line with UNFCCC reporting guidelines, and do not include potential overseas impacts embedded in the UK's consumption of food (Garvey et al. 2021). For example, the land sector pathway in the Climate Change Committee's (CCC) Sixth Carbon Budget depends on a shift of over 20% of the UK's grazing land to forestry and bioenergy (Climate Change Committee 2020). However, their calculation assumes that trade flows remain the same, meaning that the country would not import more to make up for lost production, but rather that people would eat less meat and dairy. Given that there is weak correlation between domestic meat production and consumption in high-income countries (Milford et al. 2019), this assumption could increase global competition for land use.

At the same time, the successive UK Governments have moved to prioritize biodiversity protection and nature recovery in addition to carbon removals (Thomas et al. 2013; Collas and Benton 2023b; P. J. Burgess and Graves 2022). This would take the form of nature-based solutions or agroecology on farmland (Carlile and Garnett 2021; Ranganathan et al. 2020). The trade-offs between the environmental benefits and yield, at least in the short term, are well-documented for these practices (Balmford et al. 2018; Poore and Nemecek 2018; FOLU 2023; Waite et al. 2024). As with land-based carbon storage, the positive outcomes of these strategies also rely on the potential for the UK population to eat less meat (A. C. Smith et al. 2023; Finch et al. 2023; Collas and Benton 2023b; Eating Better 2019; NFS 2021). In short, the UK's simultaneous efforts to make land available for afforestation while also encouraging agroecological practices create a potential conflict between carbon storage and domestic food production.

The mechanism for implementing the UK government's land sector objectives is known as the Environmental Land Management schemes (ELMs), which aim to transition the UK away from the EU Common Agriculture Policy (CAP) following Brexit promising 'public money for public goods' (DEFRA 2020). The list of potential paid interventions is long, though there is a focus on improvement of on-farm biodiversity and carbon storage, and reducing agricultural inputs (DEFRA 2023b). ELMs therefore represents a shift toward paying for environmental outcomes rather than food production.

In 2019, most farms required income from the UK's Basic Payment Schemes and Agri-Environment Schemes (the predecessor of ELMs, aligned to CAP) to be profitable (Collas and

Benton 2023a). Given the importance of subsidies in overall farm profitability, farmers are indeed responding to the incentives offered in ELMs (DEFRA 2025c). This emphasizes the need to assess possible trade-offs between emissions reduction and productivity for subsidized interventions.

Across the dozens of actions the government will pay for, the largest payment per hectare is for afforestation—taking land out of production to plant trees for carbon sequestration, emissions reductions, and nature recovery. These incentives align with the CCC's Carbon Budget strategy to take land out of production for carbon storage, but do not explicitly account for the possibility that food may have to be produced elsewhere to make up for this displaced food production (Searchinger et al. 2019, 2023). That is, when land is used to produce food, feed, or fiber, rather than some other use, such as storing carbon in a native ecosystem, there is a carbon opportunity cost (COC).

Emissions factors for the COC were originally calculated in Searchinger et al. (2018) for a given product using global or regional average carbon stocks across all land where it is produced. For a given crop, the COC represents the average difference between native potential carbon stocks and agricultural carbon stocks on all land where that crop is produced (Searchinger et al. 2018). This carbon stock differential is then annualized over approximately 30 years because, while deforestation is instantaneous, anthropogenic land usage occurs over many decades. The annualization therefore allocates an annual impact to the ongoing use of agricultural land. We use regional COC factors (Wirsenius et al. 2025), which implies that we assume lost production will be replaced elsewhere in Europe. Given the majority of the UK's beef (AHDB 2024) and feed (DEFRA 2024c) imports come from within the EU, we argue that this is a reasonable assumption. However, we note that the proportion for beef imported from Australia is growing.

Including COC as a source of emissions from the consumer side would disincentivize consumption of land-intensive products. From the production side, however, the COC incentivizes using land more efficiently, and recognizes that the opportunity cost of taking land out of production in one place would require clearing land elsewhere to make up for it (other supply and demand factors being equal) (Hanson and Ranganathan 2022). These emissions factors are typically annualized over a period of approximately 30 years to recognize that, while land use conversion is instantaneous, agricultural land is used as such for many years. COC factors are applied as an exogenous parameter that represents the average carbon impacts of marginal changes in production, as opposed to spatially explicit indirect land use change predictions. Additionally, the Greenhouse Gas Protocol's recently published Land Sector and Removals Standard requires companies to report the COC of the land-based products in their supply chain (WRI and WBCSD 2026). This recent development strengthens the case for the consideration of COC in farm-level decisions.

Here we develop and demonstrate a heuristic tool that incorporates the COC of food output lost due to the implementation of certain on-farm interventions. We call this tool the Farm Productivity Evaluation Tool (FarmPET) because it explores the value of a farm's productivity relative to alternative land uses. FarmPET is an exploratory tool, allowing users to assess possible climate consequences of on-farm decisions. As such, this is not intended as an attributional inventory or trade model, but rather as a transparent mechanism that examines how global land use competition could influence the net climate impacts of farm management decisions incentivized by emergent farm subsidy schemes using consequential accounting principles.

5.2 Methods

Our tool consists of modules for pasture-based beef and crop farming. The purpose of this tool is to transparently estimate the climate effects of both land use change and GHG emissions with respect to an intervention on either grazing land for livestock or cropland used to produce livestock feeds. The data inputs, mathematical steps, and model outputs for the livestock and crop modules are shown in Figure 5. 1. For each module, the user may either rely on default data, or input their own baselines to explore the sensitivity of each parameter. The modules calculate the total food produced and GHGs per hectare per year. Instructions for inputting data into each module can be found in Appendix II.1. Users can then simulate different interventions based on ELMs incentives.

To demonstrate the use of this tool, we examine the yield and climate effects of afforestation of grazing land for livestock, and of a shift to various agroecological practices for crops through two separate modules with the same underlying principle. We include these scenarios as policy-relevant examples; the ongoing narrative is such that marginal grazing land should be afforested, and crop production must shift to agroecology. The default data, emissions factors, and crop yields are in Appendix II.2.

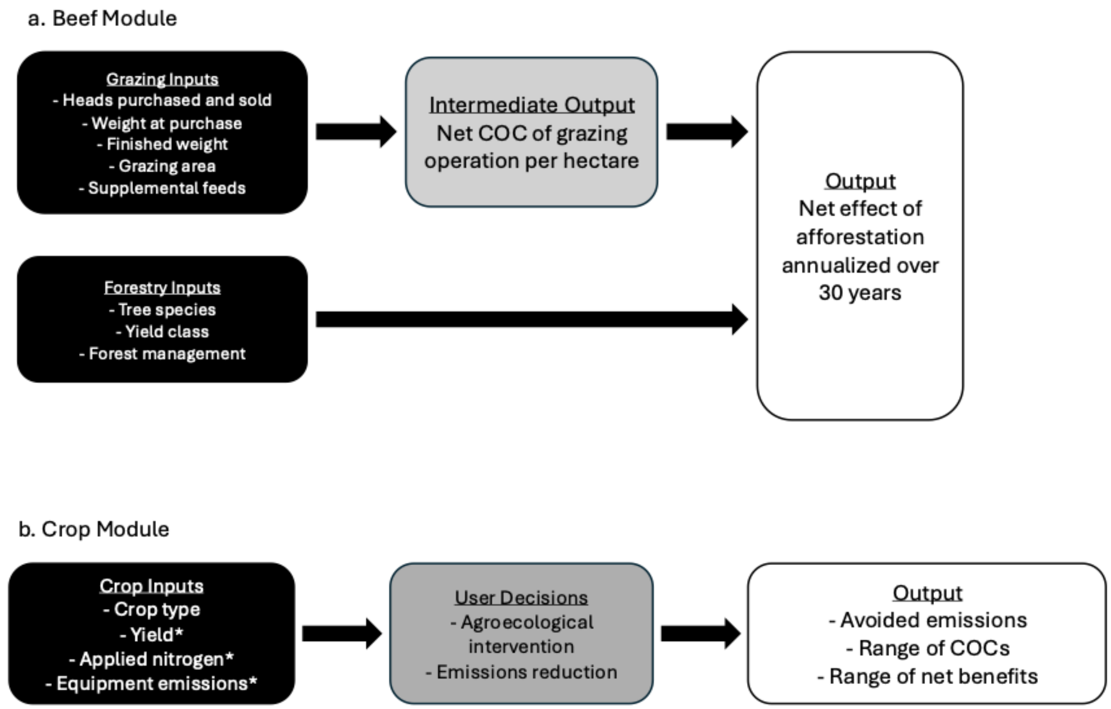

Figure 5. 1 Schematic diagram of the inputs, user decisions, and outputs for the cattle module with an afforestation intervention (a) and crop module with an agroecological intervention (b). User inputs (black) can also use default national average data. Intermediary outputs are shown in light gray, user decisions are denoted in dark grey, and outputs are shown in white.

5.2.1 Crop module

To understand the effect of alternative farming practices on crop yields, we conducted a systematic review of several meta-analyses and comparative life-cycle assessments (LCAs). It is generally understood that shifting from conventional to 'conservation' or organic agricultural practices results in lower yields, at least in the short term, particularly in the Global North (P. Burgess et al. 2019; FOLU 2023). However, these effects are highly variable by crop and region. As such, we conducted a systematic review of papers that reported percent changes in yields for crops in the UK between conventional and alternative practices.

We searched on Google Scholar using the terms ‘conservation farming yields,’ ‘no till yields,’ ‘organic yields,’ ‘intercropping yields,’ and ‘yield meta-analysis.’ We screened the results and supplements of relevant papers and extracted the yield effects by crop and practice. We also consulted several publications with literature reviews containing references to relevant papers, which we also screened (CE 2024; Poore and Nemecek 2018; FOLU 2023). Papers were excluded if they did not contain any yield data for the UK. We included papers that had UK yield data for crops used for cattle feed to focus on the ruminant system. We excluded forage crops because interventions relevant to these products are classified as ‘grassland management,’ whereas this tool focuses on ‘cropland’ interventions. Supplement B of Appendix II contains citation information for the papers included, as well as justification for excluded papers.

We looked for examples that contained information about on-farm emissions and yields in the same publication, however we did not find many, highlighting a gap in the literature to be addressed by future research. For the purposes of this exercise, we include the percent reduction of GHG emissions as a user input rather than a pre-programmed value. This decision is aligned with how on-farm decisions are made, based on forecasted emissions reductions as opposed to measured results. By including this value as a flexible input parameter, users can run various scenarios to explore, for example, the level of emissions reduction required to achieve a net benefit.

The tool’s crop module allows users to select a crop and alternative farming practice from a dropdown list. They may then either use the default yield, or input their own if the yield of the farm in question is known. The tool then requires the percent of GHG emissions reduced due to the intervention. This value would be estimated by the user based on reasonable assumptions. For example, if an intervention involves eliminating nitrogen fertilizers with no other changes, and fertilizers make up half of the baseline emissions, it would be reasonable to claim a 50% reduction in emissions.

5.2.2 Beef module

To explore decisions pertaining to the afforestation of grazing land, we first calculated the carbon payback period for a beef finishing operation at an experimental farm in Devon, UK. When grazing land is taken out of production for afforestation, the COC due to foregone food production is immediate, although the carbon sequestration of the planted forest happens over time. This creates a carbon debt that takes a number of years to repay. We compare the de-annualized COC per hectare with forest carbon storage over time. The COC of foregone food production is calculated simply as the quantity of beef lost per hectare multiplied by the regional emissions factor for European cattle grazing (Wirsenius et al. 2025), minus the COC of any feeds produced outside the farm. These values are represented in units of kg CO_2e per hectare. This flexible approach allows users to explore the effect of changing management decisions to understand the implications for farms of varying productivity. We use data from a published LCA for the calculations in this paper, though the inputs can be modified to reflect any other real or illustrative farm (Jebari et al. 2025). We also note that this analysis uses regional COC factors calculated for Europe, as opposed to global, in recognition that most imports of beef and grain come from the EU. Thus, we effectively assume lost production is replaced from somewhere within Europe.

We then use the Ecological Site Classification v4 (ESC4) online map to input the location of the farm (Forest Research 2016). This will present a range of optimal tree species that could be planted in the specific region, along with the yield class of that tree for that area. This step must be done online, and the yield class and species must be input manually using dropdown lists. The tool pulls the annual carbon sequestration rates for the designated tree species and yield class from a Woodland Carbon Code dataset (WCC 2024).

To compare the total carbon storage from afforestation over time with the COC of lost food production, we calculate the annualized carbon sequestered over thirty years. We use thirty years because this roughly aligns with many mitigation strategies that have targets in 2050, including that of the UK CCC. The annualized carbon storage of the forest is then compared with the annualized COC of lost food production. This calculation can be used to understand whether grazing or carbon storage is the most optimal use of a piece of land.

5.3 Results

5.3.1 Yield uncertainty impacts the potential climate effects of cropland interventions

The review of meta-analyses and LCAs resulted in data from 27 relevant publications for 8 different crops across 7 different farming practices. The summary data from the review is shown in Appendix II.3. Appendix II.4 contains definitions for the farming practices included.

The changes in yields for different practices are shown in Figure 5. 2 as box plots. This figure not only shows the magnitude of potential changes that could happen to crop yield for a given management practice, but also the relative abundance (or lack thereof) of data available for each practice. For example, there is a great deal of data for yield effects of organic production in the UK, but very little for fertilizer management and application of crop residues. Practices with very little data suggest the need for more evidence, and results generated using the tool for these practices should be interpreted with caution. We further note the outliers on both ends of the range for no-till, and include a brief discussion of these results in the Appendix II.5.

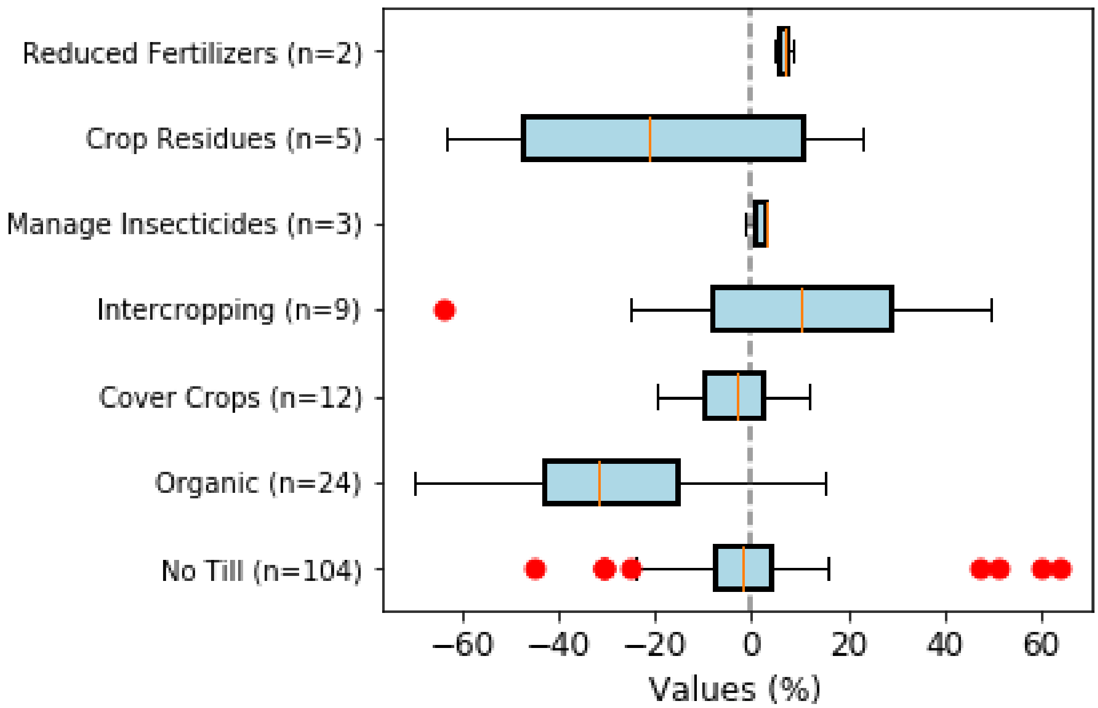

Figure 5. 2 Range of percent changes on yield relative to conventional crop management practices for a range of interventions in the UK. A negative value denotes a drop in yield, whereas a positive value represents a yield gain.

Based on the information provided by the user, the tool generates an image such as Figure 5. 3, which illustrates the relationship between the change in COC as a function of the potential change in yield, the avoided emissions (which is independent of yield change) and the net impact, which is a difference between these two values. This figure is an example for the shift from conventional to organic barley production.

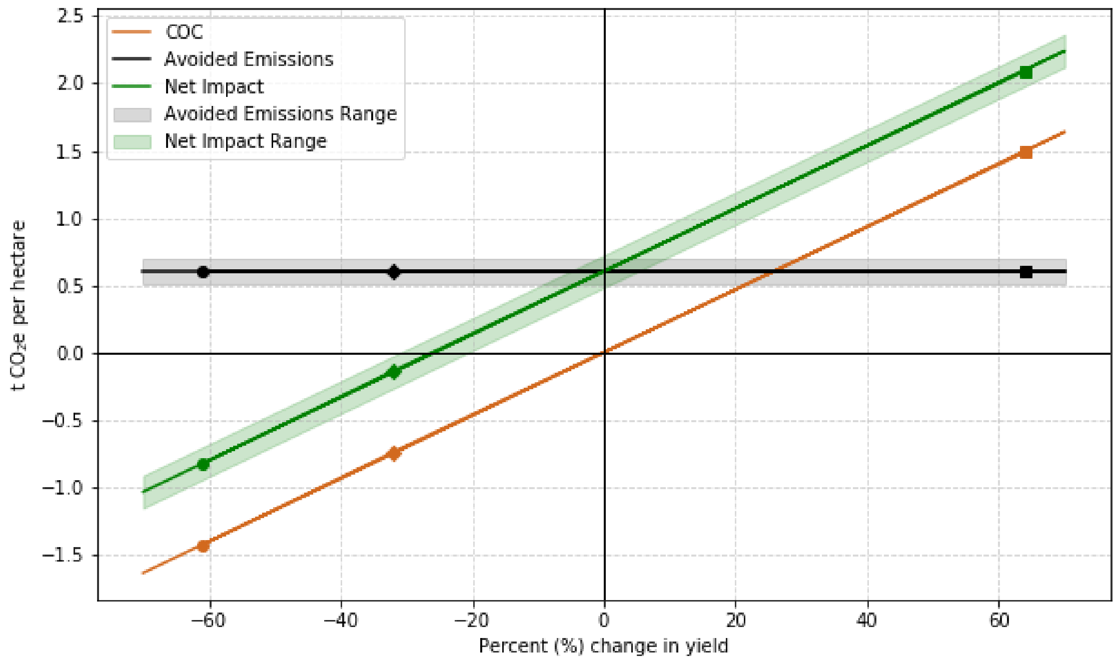

Figure 5. 3 Example of the avoided emissions (black), effect of yield change on COC (orange), and the net GHG impact (green) for barley where the farmer shifts to using organic production at the lower bound (circle), average (diamond), and upper bound (square) values as extracted from the literature. In this scenario, the shift to organic production results in a 50% decrease in on-farm emissions. This diagram shows the wide range of potential net costs and benefits, depending on the outcome of the change in practice with regards to yield. To test the sensitivity of the avoided emissions input by the user, the shaded regions show the effects of a range of values from 40% to 60%. The point at which the net effect becomes negative therefore ranges from a 20% yield loss (with 40% avoided emissions) to 30% (with 60% avoided emissions). This scenario is illustrative based on a hypothetical barley farm and does not represent a prediction for a real farm.

The points on the lines represent the lower (61% yield loss), average (32% yield loss), and upper (64% yield gain) percent changes to yield from the literature. Note that, for approximately half of the values, the net effect (green) is negative. This means that, despite the wide range of possible yield effects, over half of the yield effect values in the literature for shifting from conventional to organic barley result in a net-negative effect given the optimistic assumption of a 50% reduction in production emissions when considering the COC of a change in yield.. Therefore, pursuing a shift towards organic barley has highly uncertain net impacts. Here we also explore the sensitivity of the output to the avoided emissions parameter input by the user. We present other example scenarios with more varied outcomes in the Appendix II.6. We include an analysis of the sensitivity to the discount rate used for the COC in the Appendix II.7 as well.

5.3.2 Afforestation outcomes depend on both grazing productivity and forest sequestration rates

For a UK beef finishing operation in Devon, we use data from a recently published LCA to examine the effects of taking grazing land out of production in favor of afforestation, which farmers would have the option to do under ELMs subsidy schemes (Jebari et al. 2025). Figure 5. 4 shows the de-annualized COC per hectare of grazed land relative to the cumulative carbon storage of afforestation over time to demonstrate the payback period for displacing food production.

The orange line represents the cumulative carbon sequestration of a forest of the best-suited species according to the Ecological Site Classification database described in the Methods. Here we use the growth rates for thinned Corsican pine trees of yield class 12. In this example, it would take about 17.5 years to sequester enough carbon to make up for the carbon lost elsewhere to replace foregone food production.

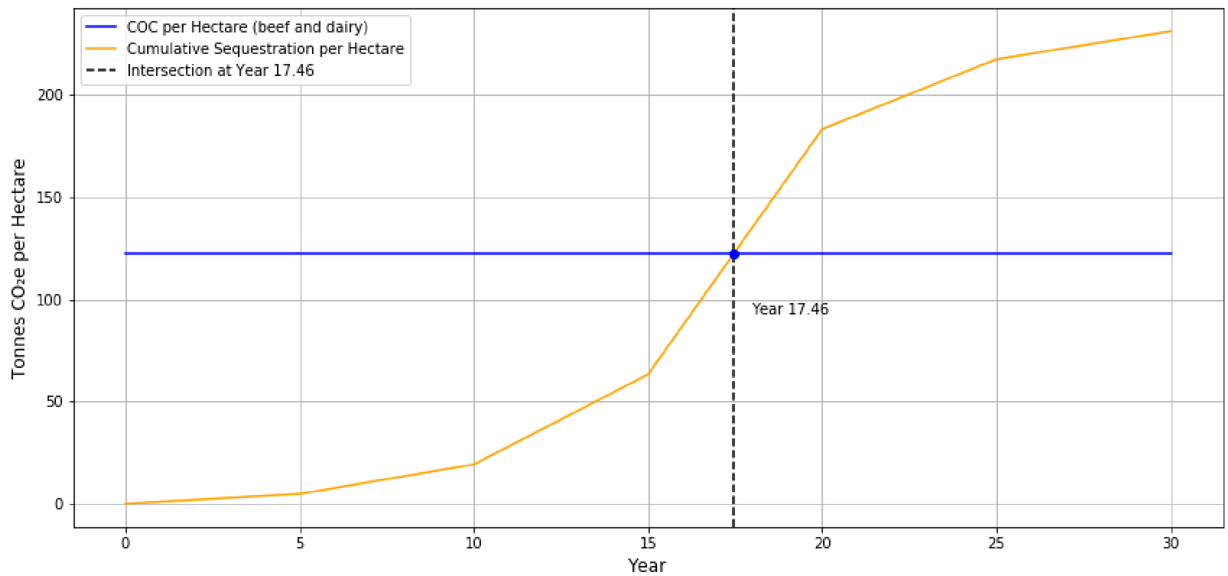

Figure 5. 4 Visualization of the payback period to sequester the amount of carbon lost due to the de-annualized COC of foregone beef production on a beef finishing operation in Devon, UK. This scenario uses data for a thinned Corsican pine forest with yield class 12. This species and yield class were chosen based on the recommended tree species for the region using the Ecological Site Classification database. Note here that the afforestation data source used does not include any uncertainty, thus we do not include an uncertainty range.

On a more efficient farm, the COC of lost food production would be greater, because more food would have to be produced elsewhere, and thus the payback period would be longer. If the forest is in a region that has high potential sequestration rates, the payback period could be shorter. These examples demonstrate the importance of the carbon storage potential relative to the efficiency of a farm.

5.3.3 The utility of COC for decision-making based on relative livestock productivity and carbon storage potential

As with the decision-making framework demonstrated by the crop example in Figure 5. 3, whether a change in practice on grazing land results in a net benefit depends on the relative impact of the intervention compared to the COC of lost food production. Table 5. 1 shows a series of scenarios in which we vary both the carbon sequestration of a planted forest (High/Low C), and the productivity of the beef finishing operation from Jebari et al. (2025) (High/Low Yield). This exercise quantifies the trade-offs between intensification and afforestation to inform decisions on the farm, as well as the net-benefit that would result from a change in land use. The tree species and growth rates used for each scenario can be found in Appendix II.1.

Table 5. 1 Scenarios to demonstrate a calculation of the annualized net impact of afforestation of grazing land as a function of both beef productivity and carbon sequestration. The baseline scenario uses the production data in Jebari et al. (2025), and the tree species recommended by ESC4 as shown in Figure 4. The other scenarios moderate the yield of the beef production by either + or – 25% and the carbon sequestration potential for afforestation. In the baseline scenario, afforestation offers a modest net carbon benefit. When a slower-growing tree (Low C) species is chosen, the net outcome becomes dependent on the beef yield.

Scenario	Farm Yield (kg beef per ha)	De-annualized Farm COC (tonnes CO_2e per ha)	C Storage (tonnes CO_2e per ha)	Net Effect (tonnes CO_2e per ha)	Annualized Net Effect (tonnes CO_2e per hectare per year)
LCA Baseline	182.6	122.3	231.4	109.1	3.6
High Yield, High C	228.2	152.9	440.7	287.8	9.6
Low Yield, High C	136.9	91.7	440.7	349.0	11.6
High Yield, Low C	228.2	152.9	122.9	-30.0	-1.0
Low Yield, Low C	136.9	91.7	122.9	31.2	1.0

In the baseline scenario, the ESC4 online tool suggested that the most optimal tree species for the location of the farm is thinned Corsican pine at a yield class of 12, as illustrated in the payback period example shown in Figure 5. 4. Over 30 years, this species would sequester 231 tonnes of carbon dioxide per hectare. Compared to the COC of the beef finishing operation, there is a small annual net benefit in converting this grazing land into forest. In other words, one could argue that the land currently used for the grazing operation would be better utilized as a forest, and the beef could likely be produced more efficiently elsewhere. When we choose a faster-growing tree species with approximately double the sequestration potential compared to the baseline, the net benefit becomes much more pronounced regardless of the efficiency of the beef production. However, the net benefit becomes a net cost when a slower-growing tree species is used. Thus, the net benefit of a change in land use is acutely sensitive to the realized carbon storage of afforestation. These examples illustrate that consideration of the COC of foregone food production due to changes in land management can influence the perceived optimal decision from a climate perspective depending on how the decision effects yield. Afforestation is therefore not necessarily a guaranteed net carbon benefit as conventional national AFOLU accounting frameworks would suggest.

5.4 Discussion

This paper proposes a quantitative mechanism for considering the COC of productive agricultural land in on-farm decision-making in the context of interventions proposed by the UK's ELMs. We argue that assessing possible trade-offs at the farm-level using FarmPET offers useful insights that can inform the implementation of interventions that minimize contribution to global land use competition. Primarily, we find that the climate benefit of an intervention depends on the level of emissions reductions or carbon storage achieved, and the magnitude of lost food production. Note that, if an intervention occurs without reducing yields, the COC would not change. Similarly, if an intervention increases yield, the farm could incur an additional benefit that would not be counted otherwise. The tool presented in this paper demonstrates how COC can be used to test productivity thresholds that would affect whether an intervention yields a net climate benefit.

We highlight the substantial uncertainty of the yield effects of shifting to agroecological practices on cropland. A wide body of literature affirms the potentially broad range of changes in yield that could occur during a shift in practice. We reviewed this literature to extract values that pertain specifically to the UK to understand the relevance at the national level of global ranges reflected in meta-analyses. We found that most UK data points across several practices suggest either a substantial decrease in yield or, sometimes, a small increase. For several crops, possible yield ranges could lead to either net negative or net positive outcomes for the same intervention, depending on the actualized effect on yield. We also explored the data availability of these yield effects and found that several practices had only one or two case studies with UK data, with much of the data coming from studies over thirty years old. This points to additional uncertainty for these specific practices with insufficient or outdated data that should be considered when making decisions.

For grazing operations, limited data availability at the farm level points to a broader gap in the literature. Our review yielded very few LCA studies with sufficient farm-level data needed for the afforestation calculations. Users with access to farm data could create realistic scenarios, though the tool was not designed to be prescriptive. Rather, the tool is meant to illustrate the trade-offs (and synergies) that arise when we consider yield, and how sensitive the optimal outcome is to changes in productivity.

The beef module relies on an external source to identify the most appropriate species of tree to plant in any given region. However, the ecology literature has increasingly pointed out that tree planting is not a panacea (Holl and Brancalion 2020), nor is it always ecologically appropriate in a given eco-region (Luedeling et al. 2019). These ecological considerations become especially important in the case of planting non-native species to maximize carbon sequestration (Kirschbaum et al. 2024). Note that whether afforestation is ecologically appropriate should be separately considered, though it is beyond the scope of this paper.

We must also consider that the impact of agriculture, particularly involving cattle, extends beyond GHGs and land use. While the analysis at hand focuses on these two factors, cattle production also has significant implications for other environmental outcomes including water use and water quality (Resare Sahlin and Trewern 2022; Wisser et al. 2024; McAuliffe et al. 2023). Future research might incorporate these additional externalities into the cost-benefit analysis framework presented here. We also note that this analysis does not directly consider the effects of reducing meat and dairy consumption, though this is a well-recognized, crucial intervention (Hayek et al. 2021; Clark et al. 2019). As we have pointed out, national climate strategies, including that of the UK, depend on reduced production and, implicitly, consumption of meat. Thus, our findings reinforce the need for simultaneous demand-side changes, though modeling such scenarios is beyond the scope of this analysis.

The tool presented here outlines the considerations needed to quantitatively understand whether an intervention might generate a net climate benefit from farm to farm. We therefore emphasize the importance of accounting for trade-offs associated with the offshoring of land use due to actions that might reduce domestic food production.

5.5 Conclusion

Using examples of the afforestation of grazing land and conversion to agroecological practices on arable land, we demonstrate that consideration of the Carbon Opportunity Cost of land can reveal a net-negative climate impact when an intervention reduces productivity. Our new heuristic tool, FarmPET, offers a transparent way to explore these trade-offs at the farm-level using default data from the literature or from a real farm.

In the case of arable farming, uncertainties in yield effects of agroecological practices dominate outcomes. We also note that most comparative LCA yield data found through our systematic review are at least thirty years old. Thus, we highlight a need for more recent comparative LCAs for a wide range of crops and agroecological practices in the UK. In our example on grazing land, the net impact is largely determined by the level of carbon sequestration achieved through tree planting. If sufficiently high sequestration rates are materialized on the farm, afforestation can generate a marginal net benefit, even on high-yielding grazing land.

In conclusion, FarmPET provides a practical way to quantify the relationship between farm-level productivity and global climate mitigation. It can be used to identify which interventions have net climate-positive results under real-world uncertainty while minimizing national contribution to global land use competition.

Chapter 6: Aligning corporate and national definitions of net zero for effective livestock mitigation policy in Europe

This chapter uses purposively sampled semi-structured interviews to explore perspectives on what net zero means for Europe’s ruminant agriculture sector, and offers options to adjust existing emissions accounting conventions to incentivize collaborative mitigation efforts across stakeholder groups. The supplementary materials can be found in Appendix III.

Aligning corporate and national definitions of net zero for effective livestock mitigation policy in Europe

Zionts, J., Allen, M., Bartlett, H.

Status: A version is under review in *Climatic Change*

Abstract

Companies and governments across Europe have adopted ambitious emissions reduction targets, frequently framed using net zero terminology. However, the assumptions, accounting approaches, and system boundaries underpinning these targets vary substantially, particularly with respect to non-CO_2 emissions from livestock. The livestock sector is widely considered 'hard to abate,' yet corporate and national climate strategies often approach mitigation opportunities and responsibilities differently. While national strategies may include reductions in livestock production or land-based carbon removals, companies with livestock products in their supply chains cannot necessarily rely on such measures to meet their climate commitments. This study examines how divergent interpretations of net zero targets shape livestock mitigation strategies and policy coherence in four European countries. Using thematic content analysis of 41 semi-structured interviews with government, industry, farming, and research stakeholders, we analyze areas of both agreement and conflict in visions for agricultural decarbonization. Across stakeholder groups, there is broad agreement that net zero emissions cannot feasibly be achieved for ruminant livestock alone using conventional greenhouse gas accounting approaches, without substantial reliance on biogenic carbon removals. At the same time, uncertainty over appropriate metrics, baselines, and sectoral responsibilities has contributed to misalignment between corporate and national climate objectives, leading to missed mitigation opportunities. We argue that greater alignment between public and private climate strategies is necessary to unlock mitigation in livestock supply chains. We highlight the potential opportunity for pre-competitive,

product-level corporate emissions reporting, alongside the incorporation of emissions intensity metrics and consumption-based accounting in national target-setting, to improve transparency, coordination, and policy effectiveness in the agricultural sector.

6.1 Introduction

Net zero refers to a state in which greenhouse gas (GHG) emissions are counteracted by removals over a specified period of time (IPCC 2018). Despite efforts to standardize target setting and reporting (Gao et al. 2014; WBCSD and WRI 2004), corporate and government entities apply different sets of assumptions around how progress towards these targets is measured, which affects the mitigation interventions incentivized as a result (Hale et al. 2022; Net Zero Tracker 2025). Furthermore, the actions required to achieve net zero vary substantially by sector. In sectors where most emissions come from energy consumption, there are zero-carbon alternatives in the form of renewable energy sources. The Science-Based Targets Initiative's Forest, Land and Agriculture Guidance states that the net zero target for companies buying and selling agricultural products is defined as a reduction of 72% of supply chain emissions (SBTi 2023). However, the mitigation potential within supply chains of arable crops is much greater than the potential of currently available mitigation interventions on ruminant farms. Ruminant agriculture will always use land and will always have some production emissions as a 'hard-to-abate' sector, especially in the context of ruminants (Edelenbosch et al. 2024; J. F. Green and Reyes 2023; Herrero et al. 2016; Wollenberg et al. 2016).

Globally, ruminant agriculture is responsible for approximately 11% of anthropogenic greenhouse gas emissions [measured using Global Warming Potential over 100 years (GWP_{100})] and uses around 70% of global agricultural land (IPCC 2018; Ripple et al. 2014). Though many acknowledge the need to mitigate these impacts, there is disagreement regarding the form this mitigation should take. While some call for the reduction of ruminant agriculture to spare land for afforestation to achieve sectoral net zero (Hayek et al. 2024; Li et al. 2024), the need persists to address the impacts of any livestock production that remains (Herzon et al. 2024; Searchinger et al. 2019). Others advocate that ruminants play an important role in planetary health and human nutrition, favoring mitigation pathways that make space for cattle and sheep (Dillon et al. 2021; McAuliffe et al. 2018). Some of these actors have also explored the use of alternative emissions accounting mechanisms for methane, which they believe would ultimately reduce the level of mitigation required by ruminant operations (Liu et al. 2021b; NFU 2022). Given ongoing debates around how best to quantify the climate and land use impact of ruminant agriculture (Simmonds et al. 2025; Zionts et al. 2025), there is a question as to how the target of 'net zero' should be applied to the sector.

The analysis presented in this paper uses 41 stakeholder interviews to explore the variety of proposed pathways to, and definitions of, net zero in the context of European ruminant livestock. We employ inductive thematic analysis to discern the emissions accounting assumptions underpinning stakeholder perspectives, and the motivations therein. This paper makes three contributions to agricultural policy. First, it provides empirical evidence on how misalignment between corporate and national climate strategies constrains mitigation in livestock systems. Second, it identifies specific points of contention in emissions accounting and responsibility allocation that limit policy effectiveness. Third, it proposes actionable adjustments to reporting and target-setting frameworks that could improve coordination across public and private actors.

We engaged 41 stakeholders across four categories: government, corporate, research, and farmers. The interviews for this study were conducted in Denmark, the Netherlands, Ireland, and the United Kingdom (UK). These countries were primarily chosen due to the high proportion of national GHG emissions and/or land use attributed to ruminant agriculture. While three of the four countries are subject to the European Union (EU)'s climate and agriculture policy, all four countries have unique national context, which we take into consideration throughout the interview and analytical processes.

6.1.1 Context in Denmark

In 2021, 25% of Denmark's carbon dioxide-equivalent (CO_2e) emissions came from the agriculture sector (European Commission 2022). Denmark exports approximately about 50% of the dairy produced in the country, but does not produce significant amounts of beef (Searchinger et al. 2021). Additionally, 60% of the country's land area is dedicated to agriculture with the majority used for livestock feed and pasture (Statistics Denmark 2025). Though it is a small country, Denmark's focus on agricultural technological innovation and high export rate contribute to its reputation as one of the more climate-efficient dairy producers in the world (Wirsenius et al. 2020).

In 2024, Denmark passed the Tripartite Agreement, which would institute a tax on agricultural GHG emissions (Ministry for the Green Tripartite 2024). The first of its kind, this agreement resulted from negotiations between the government, farmer interest groups, and environmental non-governmental organizations (NGOs). The tax serves as a mechanism to meet the goal of Denmark's 2020 Climate Act to reduce national GHGs by 70% by 2030 relative to 1990 levels, and to achieve climate neutrality by 2050 (Denmark Climate Act 2020).

We include Denmark in this study to understand the perspectives around this novel policy development, and to explore how stakeholders view the implications of the tax given the efficiency of Danish production.

6.1.2 Context in the Netherlands

In 2022, agriculture was responsible for 15% of Dutch GHG emissions (CBS 2022). Additionally, half of the national land area is dedicated to agriculture, with about half of this area used for dairy production (CBS 2020). The Netherlands is also one of the top dairy producers and exporters in the world (ZuivelNL 2024).

In recent years, intensive dairy farming and fertilizer use has contributed to high levels of nitrogen runoff leading to policy interventions to mitigate risks to Dutch nature reserves (Stokstad 2019). These limits on agricultural expansion and nitrogen pollution driven by lawsuits from environmental NGOs sparked significant farmer protests at the end of 2019 (Hill and Weulen Kranenbarg 2025). Furthermore, the Dutch government has announced farm buyout schemes in an attempt to reduce livestock numbers and thereby make progress on EU climate, water, and biodiversity targets (Boezeman et al. 2023).

We include the Netherlands due to the contentious nature of implemented policy interventions aimed to reduce the externalities of the agriculture sector, which stands in contrast with the significant role that agriculture plays in the Dutch economy.

6.1.3 Context in Ireland

With less industrial activity than Denmark and the Netherlands, Ireland's agricultural sector accounts for 38% of national emissions measured using GWP_{100}, over 70% of which come from methane (EPA 2025; Government of Ireland 2025). Nearly 60% of Ireland's land area is used for agriculture (Teagasc 2017). 80-90% of Irish beef and dairy is exported, thus ruminant livestock is a significant driver of the economy (ITA 2024).

Given the significant contribution of Irish agriculture to national emissions, there are several key reports and strategies around how best to measure and mitigate the environmental impacts of ruminant production. The national Climate Action Plan to achieve climate neutrality by 2050 proposes efficiency improvements and technological interventions, as well as a widespread shift to organic farming to meet national targets (DoAFM 2022; Government of Ireland 2025). To address the overwhelming proportion of agricultural emissions resulting from ruminant methane, research efforts have explored the case for accounting for the short-lived properties of methane through a 'temperature neutrality' approach. One study finds that a temperature-based definition of climate neutrality as measured using warming-based metrics offers the only feasible pathway to meet sectoral targets (Bishop et al. 2024; Styles et al. 2024). Another makes the case that doing so would problematically grandfather historical methane emissions, favoring the agriculture sectors of wealthier nations (Duffy et al. 2025). Critiques of warming-based accounting approaches such as this are well-documented and are a key theme throughout the interview analysis (Meinshausen and Nicholls 2022; Rogelj and Schleussner 2019).

We include Ireland due to the large contribution of agriculture to the national emissions profile relative to other countries, and the ongoing national discourse around what climate neutrality means for methane mitigation.

6.1.4 Context in the UK

UK agriculture in 2022 accounted for 12% of national GHGs, a much smaller proportion relative to the other countries included in this study (DEFRA 2025a). However, agriculture uses nearly

70% of the country's land (DEFRA 2024b), over 60% of which is used as pasture (DEFRA 2024a). Another 20% is used to produce livestock feed. In total, over 80% of the UK's agricultural area is used for animal agriculture (DEFRA 2025b; WWF 2022). Despite the pressure animal agriculture puts on the UK's land resources, the country is a net-importer of beef and dairy products unlike the other countries included in this study (AHDB 2025). Furthermore, an area of land overseas equal to the size of the UK is required to support the UK food system (National Food Strategy 2021).

Following the UK's exit from the EU (Brexit), the government developed a replacement for the EU's Common Agricultural Policy (CAP) farm subsidy scheme. The Environmental Land Management scheme (ELMs) offers farm subsidies for various activities that include shifting to agroecological practices or organic production, peatland restoration, afforestation, and nature recovery (Baker 2024). Additionally, the Climate Change Committee (CCC) maps out sectoral pathways to achieve a net zero economy in the Seventh Carbon Budget. The strategy for agriculture includes a combination of emissions-reducing technology and improved crop yields, but the strategy mainly relies on livestock herd reductions (CCC 2025). The latter intervention would likely make land available for the carbon-storing opportunities incentivized by ELMs. However, the agriculture sector never reaches net zero on its own under the CCC's carbon budget. Rather, agricultural emissions are reduced by approximately 45% while most other sectors approach zero. Assumed biogenic and geologic removals are used to counteract remaining economy-wide emissions by 2050.

We include the UK in this study to explore perceptions of ELMs, and the implications of the focus on land-based carbon storage for the future of UK ruminant agriculture.

6.2 Methods

6.2.1 Data collection

Participants were contacted through the authors' networks and were categorized into one of four groups shown in Table 6. 1. We intended to engage stakeholders representing a range of views as discerned through publicly available information. This method of purposive sampling of experts and decision-makers is a recognized tool for examining causal mechanisms in social science (Soest 2023). Efforts were made to include similar quantities of participants within each country and stakeholder group, however availability and willingness to participate varied and thus affected representation for certain groups. Some of the interviews were set up by partners within each country, thus we do not have an estimate of the number of stakeholders contacted.

Table 6. 1 Descriptions of stakeholder groups, and code used to anonymously identify participants.

Stakeholder Group	Code	Description
Government	GO	Representatives from government agencies and ministries relating to climate, environment, or agriculture
Corporate	CO	Employees of meat and dairy processors or retailers, or representatives of corporate trade unions
Farmer	FA	Beef and/or dairy farmers, or representatives from farmer interest groups and trade unions
Researcher	RE	Academic or NGO researcher in the fields of climate science, agronomy, or environmental economics

The first author conducted all 41 semi-structured stakeholder interviews in English between March and July of 2025. Most interviews were held in person, with 11 conducted virtually. Each interview took approximately one hour. The interviews were recorded and transcribed using Microsoft Teams. The number of interviewees in each country and stakeholder group are summarized in Table 6. 2 below. This research was approved by the University of Oxford's Central Research Ethics Committee (Reference Number SOGE C1A 24 127). Participants consented to the use of audio recording and anonymized transcript generation. A general guide of interview topics and the participant consent form are included in Appendix III.

Table 6. 2 Number of study participants by country and stakeholder group, and code to identify stakeholder nationality.

Country	Code	Government	Corporate	Farmer	Researcher	*Total*
United Kingdom	UK	2	2	4	2	***10***
Ireland	IE	3	1	2	4	***10***
Netherlands	NL	1	4	2	1	***8***
Denmark	DK	1	5	2	5	***13***
Total		***7***	***12***	***10***	***12***	***41***

6.2.2 Data analysis

After all interviews had been conducted, the first author anonymized the transcripts using pseudonyms based on the nationality and stakeholder group of each interviewee (e.g. UK.GO.01 for British government official No. 1). During the anonymization process, the data were also cleaned to correct transcription errors. Though the data are anonymized, the authors will not be sharing full transcripts as certain details shared in the interviews, such as affiliations or publications, could be used to identify participants.

The cleaned and anonymized transcripts were then analyzed using inductive thematic analysis in the NVivo coding software. The inductive approach allows codes and, ultimately, themes to emerge from the data itself, as opposed to a deductive approach in which codes are pre-determined. Inductive coding is most appropriate when developing new theoretical insights, as is the aim of this paper, as opposed to testing existing theories (Bihu 2024).

Per the conditions of our ethics approval, participants were contacted following data analysis to ensure the quotes chosen are sufficiently anonymized.

6.3 Results

The inductive analysis of the interview data yielded 13 key themes, to which 77 codes were allocated. Most quotes were categorized with multiple codes. The themes are summarized in Table III.1 in Appendix III to provide a high-level overview of the analysis, and to illustrate the range of perspectives represented in the data. We note that not every code includes data from all countries or stakeholder groups due to the semi-structured nature of the interviews as some topics were not relevant to all interviewees.

From this process, we developed three policy-relevant insights, which we explore in the following sections. However, one additional finding warrants discussion at the outset regarding our initial question on how stakeholders develop definitions of sustainability for ruminant agriculture. Across all stakeholder groups and countries, 29 out of the 41 interviewees expressed the sentiment that their country's beef or dairy production system is sustainable, or even the most sustainable, as illustrated by the following representative statements:

> *Are we not the most climate-efficient production of milk? For instance, if we close down our milk and then it starts up in Indonesia or whatever, then is that a benefit to anybody? (DK.RE.01)*

> *Our research will continue to show us as an example that we are really, really low, certainly in the top two or three countries, if not the first, in relation to carbon foot-printing per liter of milk. (IE.GO.02)*

> *I mean, here in the Netherlands, we see a lot of issues on nitrogen and methane production and stuff like that, but in the other hand, we can produce dairy really efficiently with one of the lowest CO2 footprints in the world, you know? (NL.CO.03)*

We need to look at the UK in the global context. You know, where is the demand for meat and livestock products? How should the UK play its role in that? We don't want to offshore our emissions, but equally we're a pretty sustainable place to grow some of these things. And if you look at the expectations in terms of climate change, we're probably less likely to be impacted than a lot of other countries are. So, in theory, we should be a good place to produce this in the future. (UK.FA.01)

While interviewees across the studied geographies indicated that their system is best, the farming practices in each country vary significantly. Ireland and the UK, for example, have a heavily pasture-based system in which approximately half of the beef produced comes from the dairy herd. Denmark and the Netherlands, however, have mainly housed dairy herds and produce very little beef outside of the dairy herd. This evidence suggests that stakeholders tend to conceptualize sustainability with their system as the baseline. As a result, entities favor emissions accounting decisions that would affirm this belief. One participant explicitly supported modifying accounting methods to benefit their country's extensive production system:

I think the way we do it now where the extensive systems look bad on the current metrics, if you did revise the metrics, I don't think the extensive systems look nearly so bad. So that would weigh in their favor, and they are sharing land with nature and the pollution, such that it is more diffuse. (UK.FA.04)

This notion of actors favoring accounting decisions that would benefit their own interests is intuitive and previously documented (Cusworth et al. 2023). However, the objective of this paper—to support the development of effective land use policy and emissions accounting frameworks—requires a deeper understanding of the subjective experiences underpinning these interests. As such, Section 3.1 examines the perspectives of each stakeholder group using a systems-mapping exercise to establish what participants see as their role in livestock sustainability, and the roles they believe other groups should play. Section 3.2 then analyzes stakeholders' scientific understanding of academic debates around methane accounting, and explores how that understanding influences the urgency with which they feel the impact of livestock must be mitigated. Lastly, Section 3.3 dissects synergies and sources of dissonance in how stakeholders define net zero, and examines the opportunities and obstacles relevant to achieving more synergistic strategies. Combined, these three results offer a qualitative measure of the distance between mitigation priorities among key stakeholders, and highlights potential pathways towards a more unified understanding of the role of livestock in a net zero future vis-a-vis the way the impacts of these systems are measured.

6.3.1 Mapping stakeholder perspectives

While coding the interview data, a trend emerged in which participants described their perceptions of other stakeholder groups and the roles people think others should play in the mitigation of agricultural emissions. Mapping these relationships highlighted sources of tension and opportunities for collaboration in the mitigation of the ruminant sector. Table 6. 3 summarizes the perceptions for each stakeholder group of the others. It is read as the perception of the stakeholder group in the row towards the group in the column. For example, corporate stakeholders feel that farmers are mainly driven by financial incentives. The number (n) of perspectives included in each summary is shown in each box. Table III.2 in Appendix III contains the interview data used for this display.

Table 6. 3 Descriptions of how each stakeholder group perceives the other groups based, and the number of perspectives included in each description. Some perspectives varied substantially by country, and these distinctions are denoted by the inclusion of the country code. The table is read as how the group in the rows perceives the group in the column.

	(CO)RPORATE	**(FA)RMER**	**(GO)VERNMENT**	**(RE)SEARCH**
CO	Market competition, shifting blame down supply chain (n=6)	Driven by financial incentives, incentives should come from companies (n=8)	Government doesn't take accountability, unstable policy and priorities (n=5)	Calls for reduced meat production are unrealistic (n=1)
FA	Lack of trust, skeptical of intentions behind corporate sustainability (n=4)	Doing their best, lack of power, stratified levels of care for the environment (n=6)	Feeling left out of policy, government is too removed from the farm, disillusioned (n=10)	Portrayed negatively by NGOs, feeling under-valued (n=5)
GO	Focus on supply chain rather than economy-wide targets (n=4)	Can get jobs in other industries (DK), won't tell farmers what to do (IE, NE) (n=5)	Trying to work collaboratively, policymaking is slow, one policy does not fit all (n=7)	Hard for policy to keep up with science, funds research on agriculture (n=2)
RE	Suspicion of greenwashing, no clear corporate strategy (n=8)	Some countries (DK) have engaged farmers, but efforts are seldom rewarded (n=11)	Shifts to organic is a back-track, metric debates are a distraction (n=11)	Green NGOs sway public opinion, NGO narrative demonizes farmers (n=5)

Though the participants' respective national context was relevant in their perspectives, we summarize the high-level findings for each stakeholder group. Overall, corporate stakeholders felt that their ability to mitigate the environmental impacts of the ruminant products in their supply chain is limited in two ways. First, there is a sentiment that if one company invests in mitigation, it would put them at a disadvantage in a competitive market. Second, there is uncertainty around the support companies can expect from the government, and instability in a landscape of constantly shifting policy guidance. These dynamics create an environment in which it is difficult for a company to discern how to invest in supply-chain decarbonization, though many recognize the inherent need to do so.

Farmers and farm-interest groups expressed feelings of being left behind by policymakers, unfairly criticized by NGO researchers, and skeptical of companies telling them how to manage their farm. Many felt that guidance coming from entities who are too far removed from the farm was not realistic or helpful. However, there was a wide range in understanding of the environmental impact of ruminants among farmers. Some were not familiar with the concept of greenhouse gases, while others were deeply engaged with sustainability research or were willing to change their practices. For example, in Denmark, environmental NGOs have a strong influence on public opinion. As a result, farmers are viewed negatively in Danish society, and they see on-farm climate action as an opportunity to improve their reputation.

Government stakeholders expressed opposing views of farmers' role in society depending on the national context. A Danish civil servant theorized that some farmers would be forced to stop farming due to the Tripartite Agreement, though they did not expect that to be an issue as farmers are hard workers and can get other jobs (DK.GO.01). In contrast, policymakers in Ireland and the Netherlands expressed that it is not politically palatable to tell farmers how to do their jobs. Additionally, while governments across Europe fund research on agricultural emissions mitigation, policymakers also said that it is difficult to keep up with the latest research given the time it takes for policies to be passed and implemented.

Lastly, academic and NGO researchers affirmed the ideas that NGOs are at least partially responsible for giving farmers a negative reputation, and that it's difficult for policy to keep up with academic debates around how best to measure emissions. Some researchers interviewed had a farming background, and echoed the sentiment that farmers lack clear guidance on how best to approach sustainable practices. Several also expressed skepticism of corporate mitigation efforts, suggesting that claims around certain interventions, such as increased soil carbon sequestration, lack numerical evidence.

From this exercise, we can develop an understanding of how differences in stakeholder perspectives might create obstacles to implementing sustainability strategies in the ruminant sector. We see from the data that there is broad agreement that farmers must change their practices, but there is contention around who should bear the financial burden. Corporations are hesitant to invest due to market competition, but policymakers struggle to offer stable incentives as they receive mixed messages from researchers as to what the 'best' strategy is. As one Irish researcher said:

> *[We have a menu of mitigation strategies], but we can't force people to eat off the menu, but that's where policies and incentives come in. (IE.RE.04)*

Thus, agreement on, and delineation of, responsibility to finance and implement changes in practices could create a foundation for more unified efforts.

There is also friction in what stakeholders see as the future of ruminant agriculture. Some research and government interviewees expressed that national climate targets should be met by scaling back levels of ruminant farming and eating less meat. However, others argued that ruminants play an important role either culturally, economically, or nutritionally. As discussed previously, there is also agreement on the perceived value of European agricultural production. Many participants expressed concern around leakage, for example:

> *I think what is dangerous here is that you say the countries that are good at producing food, they stop doing that, and somebody else has to because people need food." (DK.RE.05)*

In other words, countries meeting national targets by reducing agricultural production may displace that production elsewhere, especially in the net-exporter countries included in this study. Resolution of the conflicting views on the dispensability of ruminant agriculture could help to align stakeholder priorities. Overall, there is rhetorical agreement that the environmental impacts of agriculture must be addressed, but there is misalignment as to where responsibility to mitigate lies.

6.3.2 Warming-based metrics and the role of short-lived pollutants

Understanding the impacts of short-lived GHGs, namely methane, is key in applying the net zero concept to cattle farming. With a half-life of about 12 years, methane's warming impact differs from that of CO_2, which persists for millennia. GHGs are typically measured based on the radiative forcing of a non-CO_2 gas relative to that of CO_2, known as the Global Warming Potential (GWP), over a given time horizon (typically 100 years). Warming-based metrics were developed as an alternative to conventional GHG accounting mechanisms to more accurately reflect the short-lived warming of methane by incorporating the rate of change of methane emissions over a 20-year sliding reference window (Allen et al. 2016; Cain et al. 2019; M. A. Smith et al. 2021). One such metric known as GWP* has sparked debate around whether it is appropriate to use in national or corporate accounting and target setting (Meinshausen and Nicholls 2022). We note that various warming-based metrics have been proposed, including GWP*, and actors also have considered the option of simply calculating additional warming impact using a climate model. While all have similar implications, interviews tended to focus on GWP* because it happens to be the most well-known warming-based metric among the stakeholders interviewed.

At the center of this discussion is the notion that warming-based metrics 'grandfather in' historical methane emissions from high-emitting countries, thus putting developing nations at a disadvantage (Carter and Urbancic 2023). Thus, this concept has attracted the attention of high methane-emitting countries such as New Zealand and Ireland in recent years, which have advocated for national targets based on warming, calculated based on GWP* (Barth et al. 2023; Wheatley 2024).

Given the importance of methane in the development of ruminant mitigation strategies, we explored each stakeholder's understanding of the physical science described above during the interviews. Depending on the level of understanding, follow-up questions aimed to map the perceived role of methane mitigation in a net zero livestock sector. We found that stakeholder's feelings toward GWP* were correlated with the extent to which they believed methane emissions should be mitigated. Respondents had either a positive or negative view of GWP*, and either felt methane mitigation was or was not urgent. We mapped these perspectives into four conceptual archetypes on the two-dimensional plot shown in Figure 6. 1. The data used to create this figure can be found in Table III.3 of Appendix III.

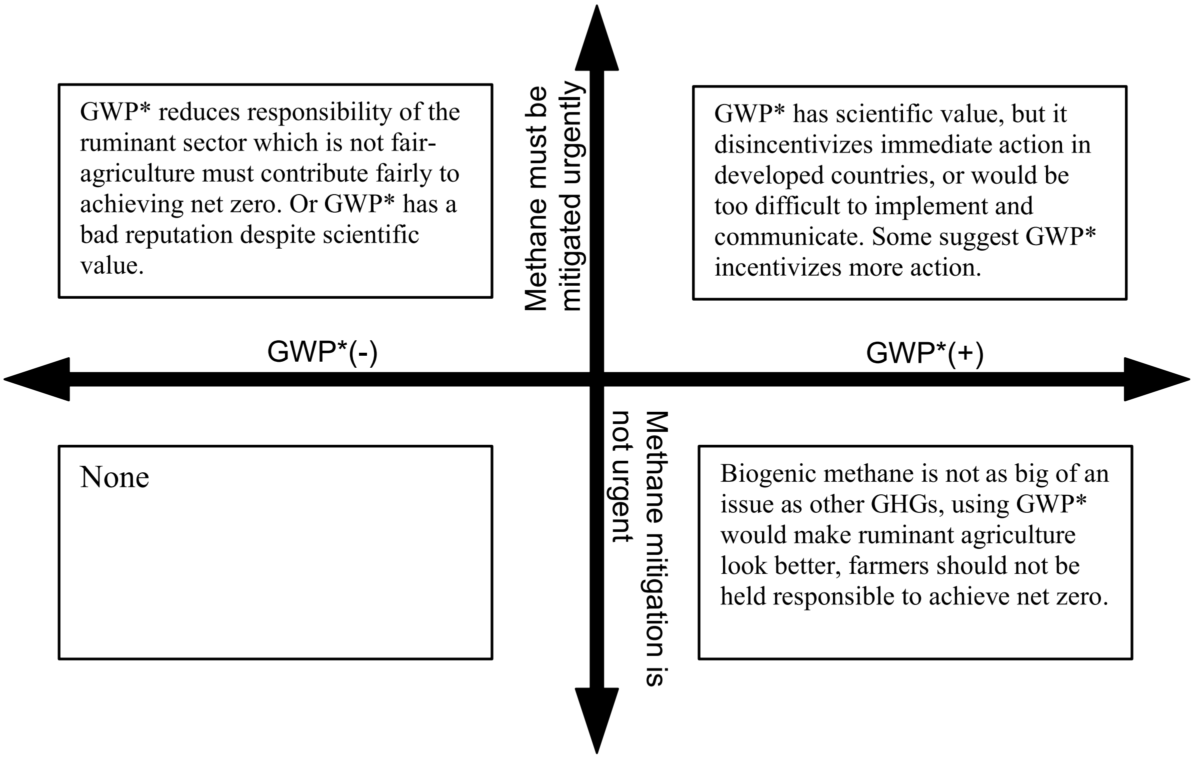

Figure 6. 1 Conceptual diagram summarizing stakeholder views towards GWP (either positive or negative), and how those views relate to the urgency with which the stakeholder feels biogenic methane should be mitigated (either urgent or less urgent).*

The distribution of interviewees across these categorizations reveals no discernable pattern in terms of which stakeholder groups are most represented — each stakeholder group is included in each category. The exception is that there were no farmers classified as having negative views towards GWP*. Though it should be noted, very few interviews with farmers involved a technical conversation on metrics that would enable them to be categorized. We also note that British and Irish perspectives were most abundant, which was expected given the prevalence of this topic in national discourse.

The first category, described as 'GWP*(+), urgent mitigation,' contained stakeholders with a scientifically accurate understanding of GWP* as assessed by the interviewer, who has significant expertise on the topic of GHG metrics. Interviewees in this category recognized the scientific value of GWP* as a metric and grasped the concept that considering the warming impact of methane more strongly incentivizes mitigation. Some in this group, however, felt that the usefulness of GWP* is limited to global or national applications to mitigate the effects explained by the grandfathering critique, or to avoid conflicts with existing accounting frameworks.

In contrast, the 'GWP*(-), urgent mitigation' perspectives often referred to the grandfathering critique as the reason for their feelings towards the metric. Interviewees in this group expressed that GWP* reduced the need for agriculture to mitigate, which they felt was unfair. Some expressed that there might be a reputational risk in aligning with a metric that is perceived to be an "easy route" (IE.CO.01). These stakeholders concerned about reputation also had good scientific understandings of GWP*. Rather, their negative feelings towards GWP* were a result of how it has been portrayed by those who have pointed to the metric as an absolution of responsibility for the livestock sector.

The perspectives of stakeholders in the third category, 'GWP*(+), less urgent,' suggested that agriculture should not be as responsible for reducing its emissions compared to other sectors, using methane's short-lived characteristic as justification. There was also a sense that agriculture is being asked to do more than their fair share. We note that many in this group felt that mitigation is still necessary, but perhaps not as much as what is being asked by a net zero target determined using GWP_{100}.

We note that no perspectives fell into the fourth category, 'GWP*(-), less urgent.' Given that the main criticism of GWP* is that it reduces agriculture's perceived mitigation responsibility, it would be unexpected for an individual to both dislike GWP* and feel that methane reductions are unimportant. However, if a company or country were planning to significantly increase methane emissions in the future, GWP* would be unfavorable, which has been a topic of discussion in Australia where plans to expand the livestock sector are prominent (Strong 2023).

We therefore argue that the lack of alignment regarding how urgently agricultural GHGs must be abated may contribute to observed disparate mitigation priorities among actors. Putting these views in the context discourse around GWP* allows us to interpret the perspectives in terms of the level of technical understanding with regards to how agricultural GHGs impact climate change. For example, a demonstrated misinterpretation of the physical science of methane and climate change is contextually important and could explain why a participant might feel that climate action in the ruminant sector is less urgent.

6.3.3 (In)feasibility of net zero for the ruminant sector

Most of the 41 interviewees spoke to a definition of either net zero or climate neutrality. A range of perspectives on the feasibility of a net zero ruminant system is shown using representative quotes in Table III.4 of Appendix III.

We draw three insights from these perspectives. First, several corporate and research stakeholders felt that removals or offsets technologies would be necessary to achieve any ambitious climate target (DK.CO.01, DK.CO.02, IE.CO.01, IE.RE.01, NL.RE.01), although some also recognized there is contention around the efficacy of this approach (NL.CO.01, UK.FA.02). Second, there was a widespread sentiment that net zero for agriculture alone is not possible, mainly because agriculture will always have an environmental impact (DK.CO.04, IE.GO.03, IE.RE.02, IE.RE.03, NL.CO.02, UK.FA.01). Yet, these targets are still set and pursued at corporate or national scales without a clear understanding of how they apply to the agricultural sector.

Our third observation is that there is friction between companies and national governments in terms of their perceptions of net zero and incentivized mitigation options. National targets for the agriculture sector can be met by reducing food production to make room for carbon storage, and increasing imports, as is the current approach in the UK's post-Brexit strategy (UK.FA.01, UK.RE.02). However, beef and dairy companies cannot easily eliminate ruminant products from their supply chains, which include production emissions across different geographies, meaning they must pursue interventions on the farm or elsewhere in their production process (IE.CO.01, NL.CO.01). A Danish corporate interviewee agreed, saying:

One of the big challenges with the national targets is that there is a fictive wall around the countries, only looking at emissions occurring within the countries. So, there is definitely, in my view, a risk to sub-optimized emissions. (DK.CO.02)

This suggests that, because companies must report emissions that occur throughout their supply chain, including from activities overseas, there is a discrepancy between what is reported at the corporate and national levels. There is further contention within national accounting, which has arguably driven misaligned farm-level incentives. One British farmer pointed out about embedded fertilizer production emissions that:

We could get rid of all our [synthetic] fertilizer [and use organic fertilizer instead] and we wouldn't budge agriculture's estimated contribution to national emissions, (UK.FA.04)

because fertilizer production emissions are allocated to "Energy and Industrial Processes." This demonstrates that certain agricultural interventions would help reach national targets, but that that the agriculture sector would not get credit for their changed behavior. However, the elimination of synthetic fertilizers would reduce emissions in corporate supply chains. But if companies hesitate to set net zero targets for their Scope 3 emissions (IE.CO.01), which would include on-farm emissions, the responsibility to facilitate mitigation would remain undefined.

Companies are especially struggling to deliver on net zero targets due to challenges with supply-chain traceability and data availability. A Danish corporate representative said:

It's very, very rare that you can actually make a direct connection between this product in a shop and the land where it's grown. And that limits us tremendously if we want to make sure we have some impact on a larger level there too. (DK.CO.05)

Some larger companies have set ambitious targets based on customer demand but lacked a clear pathway to achieve them. Thus, some have had to backtrack on their commitments, leading to public backlash. As a result, another Danish corporate representative said:

> *We haven't set any official targets. We have been very careful about that. Because from our point of view, when we say we have a goal, we have to be sure we can reach this. (DK.CO.04)*

At the same time, researchers continue to debate how to define a net zero agricultural system, and national policies lean towards strategies that outsource production. Meanwhile, some pointed out that these prioritization conflicts are not sending signals to implement what is possible, further delaying action. For example, an Irish corporate stakeholder thinks:

> *There are so many differences within sustainability and how we report it that we're spending more time and energy on reporting rather than actually doing or making change. (IE.CO.01)*

An Irish policymaker agrees, saying:

> *It doesn't really matter what definition of neutrality, the level of reduction, or how much you have to reduce, it's actually get on with reducing is the big sticking point… so the debate here creates an opportunity for inaction. (IE.GO.01)*

To summarize, there is no unified understanding of what a sustainable ruminant system should look like. For those able to recognize that the required direction of travel involves rapid and immediate mitigation, responsibility to act is shifted down the supply chain such that farmers who are willing to decarbonize their practices are not financially empowered to do so. In a sense, the perfect has become the enemy of the good. While the sector waits for clearer research, policy guidance, and corporate incentives, meaningful mitigation opportunities are being overlooked.

6.4 Discussion

This study identifies key sources of misalignment between corporate and national climate strategies in the livestock sector and explores their implications for policy design. Our findings highlight three key barriers to effective mitigation: unclear allocation of responsibility across actors, inconsistent emissions accounting frameworks, and conflicting interpretations of sectoral targets. Based on our analysis, we offer policy suggestions that would align mitigation priorities and encourage more collaborative efforts across stakeholder groups towards the shared goal of a more sustainable livestock sector.

6.4.1 Corporate emissions reporting as a license-to-operate

From the perspective mapping exercise, we found that many companies have set ambitious targets to decarbonize their supply chains, but delivering on those targets requires substantial investments, which would put them at a disadvantage in a competitive market. Thus, further incentives (or penalties) are required from government, though some felt that policymakers are too far removed from the farm, making it difficult for them to effectively legislate. Additionally, legislation is slow, and the technical opportunities for agricultural mitigation are still developing. Many farmers are willing to change their practices, but they feel left behind by the policymaking process. Furthermore, there is broad agreement that the financial burden to mitigate should not be on the farmers.

In response to these tensions, we propose that national and EU policies require pre-competitive product-level corporate emissions reporting. In other words, to have access to the European market, companies in the livestock sector should be required to report emissions for their products or live animals just as they must comply with health and safety requirements. For this level of reporting, companies must overcome two substantial obstacles. First, they must invest in tracing their supply chains, which is difficult in industries with many steps between producers and consumers, as is the case in the beef industry. The second obstacle is the collection of emissions data on the farm, which must then be communicated down the supply chain. It is important, however, that this stipulation does not simply cause companies to shift their suppliers to those that already have (or report) lower emissions. Rather, as outlined in the Science-Based Targets Initiative's Food Land and Agriculture Guidance, companies should engage their suppliers to incentivize and facilitate improved practices (SBTi 2023).

The Danish dairy sector exemplifies the benefits of supply chain visibility. From the interviews we learned that, in Denmark, dairy cooperative processors have close relationships with their farmers because the cooperative visits the farm every day to collect the milk. Additionally, farmers have a financial stake in the company's activities. Given that the suppliers are well known and rarely change, the processor has the incentive to invest in their suppliers' transition to more sustainable practices and to collect relevant data to show evidence of their efforts. This stands in contrast with the beef sector in the UK, for example, where farmers sell to different processors depending on changes in price. Additionally, beef cattle take much longer to rear, but the buyer is only known at the point of sale. This limits corporate incentives to invest in their suppliers because they constantly change. However, from the interview data, we saw that there is appetite from corporate stakeholders to collaborate with one another. Our proposed reporting requirement would encourage this collaboration while leaving room for government to support with both incentives and penalties to ensure compliance.

6.4.2 Disaggregated emissions reporting

Divergent views on methane accounting create uncertainty for policymakers and companies, limiting the effectiveness of mitigation strategies. Many stakeholders felt that methane should be considered using alternative metrics to better account for its short-lived nature. Some of these individuals felt this way because they saw it as partially or fully absolving the ruminant sector of its responsibility to mitigate, while others understood the scientific value of counting methane in this way to more accurately convey its contribution to warming.

We therefore suggest that emissions should be disaggregated by GHG such that entities may use a warming-based metric alongside other conventional metrics. While we recognize the concerns around warming-based metrics in an attributional sense, these metrics are useful in consequential accounting when projecting the impact on future warming of an intervention. These adjustments would inform prioritization of the interventions that would most effectively minimize their contribution to *future* warming, irrespective of their contributions to historical warming. Understanding the warming outcomes of interventions is useful given the temperature-based target in the Paris Agreement (UNFCCC 2015). However, it is also necessary to push back on the apparent presumption that once an entity has reached some definition of net zero, they are no longer required to contribute to the mitigation of climate change. Other studies suggest scientific consensus that this would constitute a constructive policy measure (Allen, Peters, et al. 2022).

6.4.3 National intensity targets and consumption-based reporting

We found that net zero for ruminant agriculture alone is perceived as an impossibility by a wide range of actors, though this does not preclude the need for ambitious emissions reductions. Differences between production-based national targets and consumption-based corporate emissions accounting frameworks create opportunities for emissions leakage and limit the effectiveness of mitigation strategies.

As a solution to this misalignment of corporate and national mitigation priorities, we propose two amendments to national emissions reporting. First, we suggest the inclusion of intensity targets for national livestock production. Intensity targets, typically reported as kg CO_2-equivalents per kg product, cannot be met by simply reducing gross production. While targets reducing domestic consumption and production may still be set, these should exist independently of targets to reduce the environmental impact of remaining livestock production. Intensity targets incentivize emissions-reducing measures on farms without sacrificing productivity, which would be in alignment with corporate mitigation priorities. This, we argue, would facilitate collaboration between companies and governments in our call for product-level emissions reporting.

As previously discussed, several European mitigation strategies involve the reduction of livestock production to achieve national net zero targets. However, these strategies could drive an increase in imports as a result. To moderate this effect, our second suggestion for national reporting is the development of a target for the embodied emissions of imported agricultural products, echoing critiques of production-based national emissions allocation methods from nearly two decades ago (Peters 2008; Peters and Hertwich 2008). The EU's Carbon Border Adjustment Mechanism (CBAM), which requires reporting of the emissions of imported industrial goods such as cement and electricity, serves as precedence for such a policy (European Commission 2026). The development of a methodology for an agricultural component of CBAM is synergistic with our proposal for improved corporate supply chain visibility and data availability.

6.4.4 Limitations and future work

Although this analysis made efforts to engage a wide range of stakeholders, the selection process was limited in several ways. Some groups were noticeably underrepresented, such as government stakeholders. Many of our interview requests were denied for various reasons including time constraints, or limitations on policymakers' ability to comment on research that is deemed political in nature.

Additionally, inductive thematic analysis is a reflexive process in which the researcher's preexisting views and biases are embedded in the analytical process. This work is, by nature, interpretive. Thus, the insights drawn from the data are shaped by the researcher's expertise and framing of the problem. On positionality, the researcher's association with certain institutions enabled access to participants, but possibly alienated others.

The primary objective of this analysis was to utilize stakeholder perspectives to propose policy interventions that would facilitate the transition to a more sustainable food future. For this work to be relevant in corporate and national policymaking, we must re-engage with relevant stakeholders. The next step is to develop a proposed emissions accounting framework based on our findings and present it to a larger group of participants. The aim of this future work would be to understand the feasibility of implementing a framework that seeks to align corporate and national mitigation priorities.

6.5 Conclusion

Based on our analysis of 41 stakeholder interviews, we have proposed and justified several adjustments to existing national and corporate emissions accounting and target-setting mechanisms. In conclusion, we reiterate how they would facilitate alignment of mitigation priorities and enable more collaborative efforts towards the shared objective of achieving global net zero emissions.

To summarize, companies and countries must report the same emissions to incentivize the same interventions. If countries can meet climate targets by downsizing domestic agricultural production and increasing imports, there would be little incentive to decarbonize existing operations or minimize leakage. Corporate targets, however, include overseas emissions within their supply chains. For countries to report national consumption-based agricultural emissions, product-level emissions data is required for imported goods. From our analysis, we find that corporate actors can collect and communicate this data, however this process is costly and therefore must be a pre-competitive requirement to ensure compliance.

While net zero is critical at the scale of the global economy, allocating responsibility to national cattle herds requires nuance given the complexity of the system and the conflicting interests of different stakeholder groups. Even if all ruminant emissions were eliminated, there are still several other externalities of the ruminant sector that must be addressed. We recognize that it is not feasible to have a food system that does not negatively impact the environment in some way. Thus, we should reframe the objective, which is to feed a growing population with the lowest possible environmental impact. Rather than setting ‘net zero’ as the target—which lacks a clear definition for livestock—stakeholders should pursue interventions that are guaranteed to reduce the impact of agriculture across several indicators including greenhouse gases. We find that the absence of an achievable pathway to net zero for livestock is at least partially responsible for delayed commitment to interventions that may not result in net zero but would push emissions in the right direction. The adjustments to corporate and national emissions accounting proposed in this paper would align priorities and encourage collaboration across the ruminant system.

Chapter 7: Discussion

This concluding chapter discusses my contributions to the literature on the role of environmental indicators in mitigating the climate impacts associated with ruminant agriculture. This chapter also includes a discussion on the limitations of the thesis, and opportunities for future work.

7.1 Key contributions

This thesis makes several policy-relevant contributions to the literature, summarized in Table 7. 1. Although the three chapters address their own distinct research questions, the motives for each paper build on one another to form a cohesive body of work. By synthesizing the findings across the three papers, I offer four standalone conclusions from my research about how rethinking our approach to agricultural emissions accounting by aligning mitigation priorities among actors across the sector might enable more effective interventions.

Table 7. 1 Summary of key findings for each empirical chapter of the thesis

Chapter	Research question(s)	Key findings
Chapter 4: The utility of novel environmental impact metrics in UK ruminant mitigation	In what ways does metric choice for GHGs and land use influence mitigation priorities in the context of the UK cattle system?	• More ambition is always better than less, regardless of metric choice • Applying the COC increases the baseline significantly, but incentivizes interventions that would have otherwise been overlooked • GWP*, under the most ambitious pathway, gives the impression of achieving net-negative emissions by mid-century through aggressive methane mitigation, but that does not last to end-of-century, reminding us that we can't ignore long-lived GHGs
Chapter 5: Integrating the carbon opportunity cost into farm subsidy schemes	How might UK farm subsidies affect the productivity of domestic agriculture, and how can we estimate the net global impact of these decisions?	• Alternative practices incentivized under ELMs have a very wide range of possible yield effects in the UK, though many LCAs are 30-60 years old and have not been replicated • The net effect of afforestation is acutely sensitive to both sequestration rates and farm productivity, meaning the tool presented can offer critical insights at the farm level when making decisions around where to apply each ELM scheme • Considering the COC in farm subsidy decisions can inform strategies that minimize offshoring land use and agricultural emissions
Chapter 6: Aligning corporate and national definitions of net zero for effective livestock mitigation policy in Europe	How do understandings of climate neutrality or net zero in the livestock sector differ across stakeholder groups in the context of European ruminant systems? a. To what extent are these definitions influenced by what mitigation opportunities are feasible for a given stakeholder? b. What are the socio-political obstacles (and opportunities) to reducing the environmental impacts of ruminant agriculture?	• Widespread sentiment that net zero for ruminant agriculture *alone* is not possible without relying on biogenic removals • Corporate actors shift blame down the supply chain, ultimately to the consumer • Corporate incentives are required in addition to policy levers to create a mix of "carrots and sticks" pushing efforts in the same direction e.g. Denmark • Fundamental misalignment between interventions incentivized by corporate and national emissions accounting frameworks inhibits effective mitigation interventions • On a more optimistic note, stakeholders widely acknowledged the need for the ruminant sector to mitigate ambitiously, and expressed interest in pursuing collaborative efforts across stakeholder groups

7.1.1 The strengths and limitations of conventional metrics

Throughout this thesis, I have constructed a case arguing that the climate sector must critically evaluate the usefulness and limitations of greenhouse gas and land use metrics based on the outcomes of the mitigation interventions they incentivize. In Chapter 2.3, I outline the scientific origins of different metrics and offer explanations as to how and why some have become enshrined in emissions accounting conventions. The literature review concludes with the argument that conventional metrics, as they are currently utilized, cannot adequately inform climate and land use policy on their own, while recognizing the potentially insurmountable challenges of replacing metrics that are already in use. Thus, it is helpful to consider the implications of incorporating *additional* indicators.

For example, Chapter 4 illustrates how including the Carbon Opportunity Cost (COC) in a national accounting framework can incentivize interventions that minimize global land use competition due to agricultural production, whereas the most impactful intervention using conventional land use metrics is to purchase feed from regions without recent deforestation. As a result, I conclude that relying exclusively on conventional metrics could limit the UK's ability to pursue strategies that contribute to global deforestation targets.

In Chapter 6, stakeholders within the livestock sector expressed the view that setting targets for ruminant agriculture using Global Warming Potential over a 100-year time horizon (GWP_{100}) does not accurately reflect the impact of changes in methane emissions on future temperature. I demonstrate this quantitatively in Chapter 4 by modeling the temperature effects of emissions from UK cattle production by mid- and end-of-century under different mitigation scenarios. The results show that, regardless of metric choice, more ambitious mitigation is always better than less. This suggests that ongoing debates may overstate the responsibility of metric choice in determining mitigation ambition. Nevertheless, consequential warming-based accounting more effectively conveys the impact of a decision on future temperature. As such, my recommendation to disaggregate on-farm emissions by GHG (see Chapter 6.4.2) would emphasize the value of calculating warming outcomes more explicitly.

Although conventional metrics benefit from being widely applied and understood, effective mitigation policy cannot rely on a single indicator, nor should a metric be used without demonstrated comprehension of what is being measured. Rather, the consideration of a range of metrics on the basis of the interventions they incentivize could lead to strategies that enable a more transparent assessment of future impacts and trade-offs. The range need not be large—just one additional number, whether it is a warming-based outcome or COC, provides substantially more information than a conventional indicator alone.

7.1.2 Ruminants in a net zero world

Within the UK's national climate strategy, the primary mechanism for reducing emissions and increasing removals on agricultural land is to reduce livestock production to prioritize biogenic carbon storage (CCC 2025; DEFRA 2018). While these strategies point to the need to reduce consumption of livestock products to make land available, diet change remains a politically sensitive topic on which policymakers are hesitant to directly legislate. Across a range of land use strategies, however, shifting diets towards plant-based proteins is widely recognized as a necessary component of a multi-faceted food systems transformation (Agri-Food for Net Zero Network 2025; Rockström et al. 2025; Searchinger et al. 2019). Land use models also tend to rely on projected reductions in meat and dairy consumption to make land available for carbon sequestration (see Chapter 2.3.6).

National ruminant mitigation has thus far relied on reduced consumption in part because ruminant emissions are otherwise considered 'hard-to-abate' (McNicol et al. 2024; Buck et al. 2023). I have also pointed out that it is not possible to have a food system that does not negatively impact the environment in some way (see Chapter 6.5). In addition to shifting diets, efforts must also be made to decarbonize and improve the productivity of the ruminant production that remains. I therefore assert that, while reduced ruminant production is certainly part of the solution, mitigation strategies should not rely so heavily on changes to domestic consumption patterns.

The grazing module of the Farm Productivity Evaluation Tool (FarmPET) presented in Chapter 5 is built on the assumption that taking land out of agricultural production for afforestation risks outsourcing production elsewhere in the absence of (and even in the presence of) global diet shifts. By applying the COC concept in the context of UK farm subsidies, I introduce a mechanism that acknowledges the value of land already in agricultural production. I do so by quantifying the trade-off between domestic carbon removals from afforestation and land use change emissions from replacing lost food production abroad. This quantitative framework fundamentally refutes the validity of assumptions around diets that underpin national land use strategies. This is not because I am skeptical of the UK population's ability to reduce meat consumption—in fact they must. Rather, diets are not changing fast enough, and there is evidence that meat consumption in the rest of the world will continue to increase (Godfray et al. 2018; Searchinger et al. 2019). Given the globalization of agricultural markets, it is important that land use policy considers potential overseas consequences of domestic land use decisions.

Chapter 6 tackles this same tension between domestic targets and global environmental impacts by qualitatively examining European ruminant production in the context of net zero targets. As one interviewee aptly said, *"We could get to net zero easily. Just don't produce anything"* (UK.FA.01). While stakeholders overwhelmingly expressed the sentiment that net zero is not possible for ruminant agriculture alone, there was simultaneous consensus that the sector must nevertheless mitigate ambitiously and immediately. My analysis concluded that, while stakeholders feel societal pressure to set net zero targets, there is no feasible pathway for a corporate supply chain in the ruminant sector to achieve said target without substantial reliance on removals of carbon dioxide. At the same time, stakeholders recognized the challenges associated with large-scale land-based removals, including a lack of measurability, dubious additionality and uncertain permanence. They also acknowledged that counteracting methane emissions with CO_2 removals is challenging given the temporal discrepancies as discussed in Chapter 2.3.3. While the sector waits for clearer guidance or a silver bullet from government and research, opportunities to reduce—but not eliminate—the environmental impacts of ruminant agriculture are being overlooked. In other words, the perfect has become the enemy of the good.

Although net zero, at least the in terms of halting further warming, must undoubtedly be the target for the global (or national) economy, there remains a complete lack of agreement on the appropriate contribution to net zero of a national agricultural sector or an agricultural company. The Science Based Targets initiative (SBTi)'s net zero target requires food and agricultural companies to reduce supply chain emissions by 72% by 2050 (SBTi 2023), a somewhat arbitrary number largely informed by scenarios that have already been overtaken by global events. Stakeholders in my interviews expressed that even this target would be difficult to meet for a ruminant supply chain. Chapter 6 therefore calls for a reframing of the role that ruminant agriculture can play in a net zero world. I propose instead that efforts must refocus on how multiple environmental impacts can be feasibly addressed while still producing food for a growing global population.

These findings align with the World Resources Institute (WRI)'s 'Produce, Protect, Reduce, Restore' framework (Searchinger et al. 2023). The world must *produce* more food on the same amount of land, which is then linked to *protected* native ecosystems elsewhere. Society must also *reduce* emissions from agricultural production, food loss and waste, and consumption of land-intensive products. If (and only if) these conditions are met, the world can *restore* agricultural land for biodiversity and carbon storage without the risk of leakage.

7.1.3 Emissions accounting for the future

In the literature review, I postulate that metrics that are used to inform decisions about the future should consider the distinction between attributional and consequential accounting mechanisms. To reiterate, attributional accounting is typically used in corporate or national inventories to measure impact within a given year. This manner of accounting necessitates the use of attributional 'pulse' metrics such as GWP_{100}. Alternatively, an entity can simply report the quantities of each gas emitted per year. However, emissions accounting frameworks that are used to quantify the environmental effects of a decision in the future, I argue, require some form of consequential accounting.

In Chapters 4 and 6, I carefully navigate the contentions around GWP* and the ethical implications of the 20-year sliding frame of reference used in its calculation. Particularly, the debate in the literature centers around the notion that historical methane emissions are 'grandfathered' for countries that increased their cattle populations in the past (Rogelj and Schleussner 2019). The idea that warming-based net zero or climate neutrality targets using

GWP* can be achieved through only modest methane reductions, some have argued, is a failure of the metric itself (Meinshausen and Nicholls 2022; Cusworth et al. 2023). This phenomenon, I argue, occurs when a consequential metric is used for attribution. Because of the dependence on an arbitrary base year, this application is inappropriate. As I explain in Chapter 2.3.2, the decision to stop mitigating once 'no further warming' relative to a recent base year using GWP* has been achieved is a (poor) policy choice. An actor could equally set a target to achieve 'maximum cooling,' and GWP* would more accurately convey the effect of that target on temperature compared to GWP_{100}.

Therefore, the observed shortcomings of mitigation strategies, which are currently blamed on metric choices in the literature, should instead be blamed on the way that targets are set. To justify this claim, consider Power's work on financial performance measurement systems as it has been applied to emissions accounting by Jia et al. (2023). Power's hierarchy of measurements is adapted in Table 7.2 (Power 2004; J. Jia et al. 2023).

Table 7. 2 Power's (2004) performance measurement hierarchy applied to emissions accounting. Adapted from Jia et al. (2023).

Performance measurement order	Application in GHG accounting
2^{nd} order Meta-measurement system	Corporate disclosure frameworks, net zero targets, other climate targets
1^{st} order Classification system	Greenhouse Gas Protocol standards, ISO standard, National inventory framework, other aggregative accounting mechanisms
0^{th} order Measurement quantum	Emissions, either directly measured or indirectly modeled

Current Direction of Travel

Bottom-up Proposed Change

According to Jia et al. (2023), measurement quanta refer to the mechanisms that estimate emissions from an activity. 1st order classification systems set the standards as to which categories of emissions are reported, and how they are aggregated. Lastly, 2nd order meta-measurement systems are target-setting frameworks based on the implementation of the 1st order system.

In the current climate policy landscape, strategies are built around a pre-determined 2nd order target such as 'net zero' or 'climate neutrality.' Companies or countries then work from the top-down, selecting a classification system aligned with the target. They then collect or model emissions data according to the required categories. However, as I found through stakeholder interviews, there is no pathway for an actor in the ruminant sector to reliably meet a net zero target that includes all Scopes. Nevertheless, companies and governments feel obligated to reach net zero due to pressures from shareholders, constituents, or international agreements. As I discuss in Chapter 6.3.3, corporate entities in the ruminant sector will always fall short of a net zero target without substantial reliance on offsets or insets, especially if the COC of land use is included as I demonstrate in Chapter 4 (Santo and Cho 2025).

I argue that the effectiveness of mitigation strategies in the ruminant sector would be improved by instead applying Power's framework from the bottom-up. Starting with the measurement quanta, an emissions baseline must include high-quality data on relevant impacts at a resolution that can capture the effect of an intervention. For example, consider a company sourcing beef from a farm using enteric methane inhibitors. If that company wants to report the emissions reductions associated with that intervention, their baseline must include modeled (or directly measured) enteric methane emissions at the farm level. This seems intuitive, but a lack of supply chain traceability and data availability generally limits corporate emissions reporting because of the option to rely on global or regional emissions factors that do not disaggregate by GHG, as I discuss in Chapter 6.

In this bottom-up approach, the 1st order reporting frameworks would only change in the sense that additional reporting mechanisms, such as consequential accounting methods, would be incorporated within existing frameworks. The crux of this recommendation lies in decisions regarding how 2nd order targets are set. Fundamentally, I suggest that activities in the land sector are not shoehorned into the same net zero targets set for other sectors for which zero-emissions alternatives exist. This is because agricultural production cannot occur without GHG emissions and other environmental impacts, yet humanity will always require some form of agriculture. As I have seen firsthand through the GHG Protocol Land Sector and Removals process, and through the interviews conducted in Chapter 6, agricultural net zero targets encourage reliance on questionable and often impermanent land-based removals because that pathway is easier than reducing physical production emissions. The fact that the Science-Based Targets initiative's net zero target for the land sector is an emissions reduction of 72%, as opposed to 100%, proves these difficulties in a sense. Nevertheless, even this target would be difficult to achieve for a company in the ruminant supply chain in the absence of breakthrough technologies.

In short, there are right and wrong uses of both consequential and attributional accounting. The best approach depends on the use case, and my inversion of Power's hierarchy constitutes a reframing of agricultural emissions accounting, which I argue is a more appropriate approach to quantifying and managing the environmental impacts of ruminant agriculture. The first step in developing a fit-for-purpose accounting framework is to define the impact being mitigated at the base of Power's hierarchy. For example, Chapter 5 focuses on how best to minimize land use competition at the scale of a farm in the UK.

The second step is to decide whether to use an attributional or consequential 1st order approach based on whether the goal is to assign impact to an entity within a given time frame (attributional) or measure the future effects of an intervention (consequential). In Chapter 5, for example, a consequential approach is used because the assessment is concerned with future impacts of taking land out of production and planting trees. Chapter 4 also demonstrates an appropriate use of consequential accounting by modeling the impacts of different mitigation strategies on future global temperatures.

The final step is to set a target against that impact that is both actionable and ambitious. My research stops short of this step in that it is not prescriptive as to what a target should be because this depends on the priorities and ambition of the target-setter. A target might aim to minimize contribution to further warming or, using Chapter 5 as an example once again, minimize global land use competition. This approach explicitly aims to avoid the setting of targets that a company or country has no feasible mechanism to achieve. This conclusion is largely based on the results of Chapter 6, which revealed that companies and countries have put off implementing mitigation options that are readily available because they would not result in net zero. At the end of the day, as one stakeholder said, "*it doesn't really matter what definition of neutrality [we use], the level of reduction, or how much you have to reduce: it's actually [to] get on with reducing*" (IE.GO.01).

By encouraging more careful consideration of measurement choices and the implications of those choices, and by setting actionable targets that incorporate forward-looking accounting conventions, I argue that this approach will enable stakeholders to *"get on with reducing."* To put this concept into action, I have applied for the Social Science Division's Sustainable

Development Goals Impact Fund to co-create a novel target-setting framework with stakeholders within DEFRA and AHDB.

7.1.4 Aligning stakeholder priorities

At the start of Chapter 1, I point out the misalignment of agricultural mitigation strategies driven by the tension between using land for agriculture and for carbon storage, and misaligned perspectives on how to best aggregate emissions of GHGs with different physical properties. Therefore, one objective of this thesis has been to examine the consequences of these sources of misalignment and, ultimately, provide a foundation for their resolution moving forward.

In Chapter 6.3.3, I identify incongruent system boundaries for corporate and national land sector emissions accounting as a key contributor to this misalignment. In summary, corporate supply chains in the livestock sector cannot easily eliminate livestock, whose emissions are difficult and costly to abate. Conversely, wealthy countries with buying power could hypothetically continue to consume ruminant products but eliminate domestic livestock production by increasing imports. The emissions of those imported goods would not be reported in the consuming country's national emissions inventory, giving the misleading impression that they have decarbonized their livestock sector.

In Chapter 6.4, I propose two modifications to national emissions accounting conventions with the aim of resolving this incompatibility. The first modification is that national mitigation strategies should include intensity targets, reported as emissions per unit of livestock product. The second recommendation is that national inventories should report the emissions of imported goods, adding agriculture to the EU's existing Carbon Border Adjustment Mechanism (CBAM), and implementing a similar mechanism elsewhere. These considerations would initiate a shift in national incentives from relying on offshored production to interventions that reduce emissions and improve other on-farm outcomes without sacrificing productivity.

There is an important global equity implication of CBAM that is somewhat unique to agriculture. Depending on the metric chosen, agricultural goods from poorer countries might have a much higher impact, putting such countries who wish to export to the EU at a disadvantage. With that being said, such a regulation could also deter those countries from following a development path through rapid and unsustainable expansion of their cattle industries. This issue does not have a simple solution, but I acknowledge that a compromise is necessary.

Corporate stakeholders and land managers have important roles to play as well. I see the alignment of emissions accounting frameworks as a precursor to the harmonization of mitigation priorities across stakeholder groups. In short, to incentivize the same interventions, entities must be measuring the same impacts and must agree on what the goals are. In Denmark, for example, financial mitigation incentives from processors complement the tax on unabated agricultural emissions per the Tripartite Agreement (see Chapter 6.1.1). These corporate "carrots" and policy "sticks" are both pushing mitigation efforts in the same direction of travel, fostering collaboration towards tangible reductions in agricultural production emissions.

The findings of all three empirical papers in this thesis shed light on the importance of considering the implications of emissions accounting decisions on target-setting. If I can impart one piece of wisdom I have found through this process, it would be this: the choice of metric or target is not nearly as important as how it is used. Companies or governments will always have the option to take the easy way out, backtrack on pledges, or place the blame elsewhere. Metrics do matter, but they cannot result in positive outcomes on their own if the fundamental will to act is not there. Confusion over metric choices, or the perception that they are somehow unfair or contested, can result in stagnation, even among stakeholders who are broadly supportive of climate action. But if the will exists to make substantive changes to how food is produced, and to understand the effects of those decisions into the future, I hope that what I've learned here could be of use.

7.2 Limitations

Because the limitations of each individual paper are discussed in their respective chapters, this section acknowledges caveats regarding normative assumptions and methodological choices made throughout the thesis.

The calculations in Chapters 4 and 5 apply an 'operational boundary,' which includes the emissions of farm inputs, but does not include the impacts of activities that occur after the farm gate such as processing, storage or transportation. Though I justify this approach in that an operational boundary focuses on the impacts over which a land manager has agency, such as the quantity and types of feed purchased or the types of fertilizers applied, certain emissions within the livestock supply chain are excluded. However, given that the analysis centers on the significance of metric choice on land use and methane emissions, the categories that would most substantially influence results are included.

This thesis is solely concerned with the greenhouse gas emissions from ruminant agriculture and does not consider the many other environmental impacts associated with agricultural production. There are well-documented trade-offs between climate and other outcomes such as water use, biodiversity, and animal welfare (de Boer et al. 2011; Broom 2019; Bartlett et al. 2024), which could influence decisions depending on the values held by the decision-maker (Waite et al. 2024). Actors juggle multiple priorities beyond emissions, and the rank-ordering of those priorities is deeply subjective. By excluding impacts beyond GHGs, my analysis is limited in its ability to inform corporate and national policy under real-world conditions.

Regarding land use metrics, there are certain normative assumptions embedded within the formulation of COC that must be acknowledged. Changes in demand affect the price of a commodity, which in turn affects supply, and vice versa. However, The COC treats production and consumption separately, and assumes that a loss of agricultural production in one place is instantaneously replaced elsewhere with a carbon cost equal to the average difference between native potential carbon stocks and agricultural carbon stocks within a specified spatial boundary (Searchinger et al. 2018).

Other approaches account for the relationship between supply and demand by modeling the economic effects of taking land out of production for carbon storage (Griscom et al. 2017; Minasny et al. 2017; Bastin et al. 2019). These approaches assume land is made available by predetermined levels of shifting diets or food waste reductions. However, if these changes fail to materialize in the real world, the alternative assumption is that reduced production increases the price of food, which causes some people to eat less. Given that global demand for food continues to increase (van Dijk et al. 2021), The COC asserts that land that remains agriculturally productive reduces the need to clear land elsewhere. The separate consideration of production and consumption limits reliance on these highly uncertain econometric relationships, while still encouraging action in a beneficial direction of travel. On the production side, the COC is reduced by improved productivity per hectare. On the consumption side, the COC is reduced by purchasing goods that require less land to produce. The COC therefore argues that consumption-side interventions alone are insufficient to manage the global competition for land use. Improvements in production are also necessary, independent of consumer behavior.

Additionally, the COC also inherently relies on the consideration of a 'no-human-activity' counterfactual, meaning that the carbon stocks of anthropogenically managed land are compared to historical unmanaged carbon stocks (or carbon storage potential into the future). Some argue that it is economically or biophysically unrealistic for certain regions to be reforested, therefore a counterfactual that includes foregone sequestration is also unrealistic (Sohngen 2025). However, the impact of activities in all other sectors considers such a counterfactual. For example, to borrow an analogy frequently used by my colleague Tim Searchinger, driving a Prius does not constitute a carbon removal because the alternative is driving a Hummer. In reality, the impacts of both vehicles are assessed relative to the impact of not driving at all, at which point the impacts of the two vehicles can be compared. As Tim would say, this is how we measure the impact of every other human activity. The COC argues land use should be subject to the same considerations.

7.3 Future work

This research has been conducted during a period of flux in the land use policy landscape in both corporate and national contexts. As a result, there are several opportunities to build on the work I have done for this degree with the aim of shaping ongoing livestock mitigation efforts moving forward. In the three years it has taken to write this thesis, the post-Brexit farm subsidy scheme in the UK, the Environmental Land Management scheme (ELMs), has undergone various consultations and transformations. Future work could involve upgrading the farm-level calculator introduced in Chapter 5 based on the activities subsidized in the latest iteration of ELMs, and to develop dairy and sheep modules. I could also validate my farm-level calculations of the net effect of afforesting grazing land with results from other analyses conducted at broader spatial scales (Collas and Benton 2023b; Chapman et al. 2025).

Additionally, I could address the limitation identified in the previous section regarding trade-offs with other non-GHG impacts. Along the lines of a report I produced for WRI (Waite et al. 2024), I could consider the implications of indicator choice for other outcomes such as animal welfare, water use or biodiversity. The latter is especially relevant given the explicit focus of ELMs on improved on-farm biodiversity.

To improve the policy relevance of the work presented in Chapter 6, it is necessary to assess the feasibility and acceptability of my proposed changes to emissions accounting conventions. As mentioned in Chapter 6.4.4, the next step is to present my proposed modifications to emissions accounting conventions to the stakeholders I have already engaged, and eventually to a wider circle of individuals. Chapter 6 has diagnosed shortcomings in agricultural emissions accounting and proposed high-level solutions. Therefore, I could refine those solutions to better suit the individuals who would be responsible for implementing them.

There is another opportunity to build on this work by further investigating the normative assumptions surrounding the COC described in the previous section. Specifically, the usefulness of my analysis could be strengthened by a better understanding of the economic relationship between domestic consumption and production of livestock products. As I point out in Chapter 5, the UK CCC's land sector strategy hinges on the afforestation of 20-30% of the country's grazing land, with the assumption that trade flows remain constant and therefore the population reduces consumption of livestock products (CCC 2025). However, in a globalized market, this assumption requires further investigation. I would approach this question by carrying out a fixed-effects regression to scrutinize the historical relationship between changes in domestic production and imported quantities of a commodity. If my hypothesis proves correct—that decreases in production have historically been met with increased imports—this would cast further doubt on the validity of the CCC's approach and would strengthen the argument for including the COC in national emissions accounting to mitigate leakage.

Finally, I call back to the high-level question presented in Chapter 1.2. I asked: *To what extent is exclusive reliance on conventional indicators hindering progress?* I show in Chapter 4 that, regardless of metric choice, more mitigation in the livestock sector is always better than less. Through the stakeholder interviews of Chapter 6, I have also found that it is not necessarily the metric itself that limits progress, but rather the discrete system boundary decisions made by those applying the metrics. Stakeholders, understandably, tend to set temporal and spatial boundaries that reduce their responsibility to act, precisely because mitigating ruminant emissions is biophysically difficult. Thus, future work could explore how considerations beyond metric choice contribute to the development of a mitigation strategy, such as cost, feasibility, or shareholder demands. To understand the extent to which conventional metrics are responsible for a lack of realized mitigation, I must first investigate the compromises that actors in the sector are willing to make to reduce the environmental impact of ruminant agriculture.

7.4 Concluding remarks

"We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."

Aldo Leopold, A Sand County Almanac (1949)

Agricultural mitigation is a wicked problem. Producing food for a growing population within planetary boundaries in a way that is socio-economically just and acceptable requires a range of solutions and cooperation from a variety of actors such that there is no singular "right answer."

There is an adage in business management that says, “you can’t manage what you don’t measure.” But the converse is not true – good measurement does not result in good management, though misleading, inaccurate or contested measurement can result in poor management. In the context of agricultural mitigation, I find that this saying provides a good framing for the key theme throughout this thesis—that mitigation incentives are affected by decisions made when measuring impact. I began with the identification of several shortcomings of conventional approaches to agricultural emissions accounting in the context of corporate and national climate strategies in the ruminant sector. I now conclude with not only diagnostics of these shortcomings, but also with recommendations to resolve them.

Chapter 4 quantified the effect of metric choice on the perceived GHG and land use impacts of ruminant agriculture in the UK under four mitigation scenarios. Most importantly, I found that more mitigation is always better than less, regardless of metric choice. Given the contentions in the literature around how warming-based metrics reduce the responsibility of ruminant agriculture, this finding affirmed that such metrics can nevertheless incentivize ambitious mitigation if they are utilized in good faith. I also demonstrated how mitigation priorities might inform metric choice, as opposed to the other way around. Currently, conventional metrics are taken as given and mitigation strategies are developed without consideration for the global implications of those interventions, or the information communicated by the metric. Instead, I argue that metrics should be chosen based on the interventions they incentivize, and whether those interventions would contribute positively and measurably to global outcomes. For example, a mitigation strategy that aims to minimize contribution to warming requires accounting decisions that can appropriately inform the effect of that strategy on temperature into the future.

The Farm Productivity Evaluation Tool (FarmPET) built for Chapter 5 demonstrated this idea by proposing a mechanism that incorporates global land use outcomes into decision-making at the farm level. I found that the net global effects of shifting to agroecological farm practices and the afforestation of grazing land are highly sensitive to both the mitigation potential of the intervention and the productivity of the farm. This exercise constitutes an example of how metrics can be utilized in a consequential, forward-looking accounting framework with the explicit purpose of addressing a prioritized impact such as global land use competition.

Following these two quantitative assessments, I felt it necessary to ground these findings in the reality of how agricultural mitigation targets are conceptualized by a variety of stakeholders. In Chapter 6, I conducted interviews with the intention to study a range of perspectives towards the future of the livestock sector, the role ruminants might play in meeting net zero targets, and what those targets might look like. These interviews showed that actors across the European livestock sector largely acknowledged their impact on the environment and their responsibility to mitigate. However, net zero targets for the ruminant sector alone were widely regarded as infeasible, especially at the corporate and farm levels. While debates continue around what contribution the industry should make towards a net zero world, stakeholders pointed out that interim opportunities to mitigate have been overlooked.

From these narratives, I proposed three modifications to the calculation of ruminant emissions to align mitigation priorities across the sector and facilitate more immediate action. These include intensity targets and consumption-based reporting at the national scale to disincentivize offshoring agricultural production, reporting of emissions disaggregated by GHG to facilitate consequential warming-based accounting, and corporate product-level reporting to better capture the effects of on-farm interventions. This proposed path forward would bring about a new set of challenges that must be overcome to deliver tangible outcomes. Namely, these challenges include the need for better farm-level data, corporate supply chain traceability, greater investment in technological interventions, and collaboration across stakeholder groups.

Based on my findings, I propose a reframing of agricultural emissions accounting in which stakeholders prioritize the impacts of ruminants on the environment that most urgently need to be minimized by applying metrics that incentivize those outcomes, regardless of whether those efforts would result in the sector or operation reaching net zero as defined using GWP_{100}. In fact, I would go so far as to say net zero is not applicable in the case of ruminant agriculture, though it must remain the objective for the global economy. I make this case because agriculture is not like other sectors, such as the energy sector, where zero-emissions alternatives exist. Additionally, most national mitigation pathways rely on decreased agricultural production to make land available for carbon storage based on assumed levels of diet change. While diet change is a critical component of solving this complex problem, we must still address the impact of ruminant production that remains. We can therefore appreciate the agriculture sector's role in meeting the material needs of humanity by recognizing that food cannot be produced without some environmental impact. At the same time, we can still hold these emitters to account in that they must pursue ambitious efforts to minimize their impact on the environment to the greatest possible extent.

This perspective on agricultural emissions accounting acknowledges Cusworth et al. (2023)'s concept of *reflexive performativity* wherein actors engage strategically with metrology, advocating for measurement choices that would benefit their interests. However, I point out that we have the ability call out those who utilize metrics in bad faith to reduce their own responsibility to mitigate. In other words, we must clearly define acceptable uses of metrics, as I have done throughout this thesis, such that they are not used to avoid or reduce responsibility. Cusworth's framing argues that actors will always choose the path of least resistance. In response, my work has demonstrated that setting targets and choosing metrics based on measurable contributions to global outcomes, rather than relying conventional metrics alone, can moderate the performativity of metrics.

In this thesis, I have explored how existing emissions accounting frameworks and conventions influence the implementation of effective mitigation interventions in the ruminant sector. I have proposed a reframing of agricultural emissions accounting wherein climate metrics are chosen based on whether they incentivize sufficiently ambitious abatement of key impacts without displacing production elsewhere. I have also demonstrated how these changes could facilitate more tangible progress by providing a basis for the transparent consideration of priorities and trade-offs. This, I believe, is what it means to put Mind Over Metrics.

References

Addoah, Thomas, Joss Lyons-White, Federico Cammelli, et al. 2025. "Is the Implementation of Cocoa Companies' Forest Policies on Track to Effectively and Equitably Address Deforestation in West Africa?" *Sustainable Development* 33 (4): 5197–213. https://doi.org/10.1002/sd.3380.

Agri-Food for Net Zero Network. 2025. *Roadmap for Resilience: A UK Food Plan for 2050*. https://www.agrifood4netzero.net/wp-content/uploads/2025/10/AFN-ROADMAP.pdf.

AHDB. 2022. "GB Animal Feed Production | AHDB." https://ahdb.org.uk/cereals-oilseeds/cereal-use-in-gb-animal-feed-production.

AHDB. 2023a. "Applying GWP* to UK National GHG Emissions | AHDB." https://ahdb.org.uk/knowledge-library/applying-gwp-to-uk-national-ghg-emissions.

AHDB. 2023b. "GB Animal Feed Production | AHDB." https://ahdb.org.uk/cereals-oilseeds/cereal-use-in-gb-animal-feed-production.

AHDB. 2024. "UK Beef Production Update: Strong Demand Continues to Drive Production and Trade | AHDB." https://ahdb.org.uk/news/uk-beef-production-update-strong-demand-continues-to-drive-production-and-trade.

AHDB. 2025. "How Much of Each Agri-Food Product Does the UK Produce? | AHDB." https://ahdb.org.uk/trade-and-policy/export-opps/continuity-of-supply.

Ahmed, Sirwan Khalid, Ribwar Arsalan Mohammed, Abdulqadir J. Nashwan, et al. 2025. "Using Thematic Analysis in Qualitative Research." *Journal of Medicine, Surgery, and Public Health* 6 (August): 100198. https://doi.org/10.1016/j.glmedi.2025.100198.

Alcott, Blake. 2005. "Jevons' Paradox." *Ecological Economics* 54 (1): 9–21. https://doi.org/10.1016/j.ecolecon.2005.03.020.

Alix-Garcia, Jennifer, and Holly K. Gibbs. 2017. "Forest Conservation Effects of Brazil's Zero Deforestation Cattle Agreements Undermined by Leakage." *Global Environmental Change* 47 (November): 201–17. https://doi.org/10.1016/j.gloenvcha.2017.08.009.

Allen, Myles. 2015. "Short-Lived Promise? The Science and Policy of Cumulative and Short-Lived Climate Pollutants." Oxford Martin School.

Allen, Myles, David J. Frame, Chris Huntingford, et al. 2009. "Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne." *Nature* 458 (7242): 1163–66. https://doi.org/10.1038/nature08019.

Allen, Myles, Pierre Friedlingstein, Cécile A. J. Girardin, et al. 2022. "Net Zero: Science, Origins, and Implications." *Annual Review of Environment and Resources* 47 (1): 849–87. https://doi.org/10.1146/annurev-environ-112320-105050.

Allen, Myles, Jan S. Fuglestvedt, Keith P. Shine, Andy Reisinger, Raymond T. Pierrehumbert, and Piers M. Forster. 2016. "New Use of Global Warming Potentials to Compare Cumulative and Short-Lived Climate Pollutants." *Nature Climate Change* 6 (8): 773–76. https://doi.org/10.1038/nclimate2998.

Allen, Myles, Glen P. Peters, Keith P. Shine, et al. 2022. "Indicate Separate Contributions of Long-Lived and Short-Lived Greenhouse Gases in Emission Targets." *Npj Climate and Atmospheric Science* 5 (1): 1. https://doi.org/10.1038/s41612-021-00226-2.

Allen, Myles, Keith P. Shine, Jan S. Fuglestvedt, et al. 2018. "A Solution to the Misrepresentations of CO2-Equivalent Emissions of Short-Lived Climate Pollutants under Ambitious Mitigation." *Npj Climate and Atmospheric Science* 1 (1): 1. https://doi.org/10.1038/s41612-018-0026-8.

Allen, Myles, Katsumasa Tanaka, Adrian Macey, et al. 2021. "Ensuring That Offsets and Other Internationally Transferred Mitigation Outcomes Contribute Effectively to Limiting Global Warming." *Environmental Research Letters* 16 (7): 074009. https://doi.org/10.1088/1748-9326/abfcf9.

Anderson, Christa, Tereza Bicalho, Elizabeth Wallace, Tim Letts, and Martha Stevenson. 2022. *Forest, Land and Agriculture Science Based Target Setting Guidance*. SBTi.

Axelsson, Kaya, Audrey Wagner, Injy Johnstone, et al. 2024. "Oxford Principles for Net Zero Aligned Carbon Offsetting (Revised 2024)." Smith School of Enterprise and Environment, University of Oxford.

Azar, Christian, Jorge García Martín, Daniel JA. Johansson, and Thomas Sterner. 2023. "The Social Cost of Methane." *Climatic Change* 176 (6): 71. https://doi.org/10.1007/s10584-023-03540-1.

B+LNZ (Beef + Lamb New Zealand). 2021. "GWP* a Key Focus of Climate Change Submission." https://beeflambnz.com/news-views/gwp-key-focus-climate-change-submission.

Baker, Jonathan. 2024. *Environmental Land Management in 2024: Details of Actions and Payments – Farming*. January 4. https://defrafarming.blog.gov.uk/2024/01/04/environmental-land-management-in-2024-details-of-actions-and-payments/.

Balmford, Andrew, Tatsuya Amano, Harriet Bartlett, et al. 2018. "The Environmental Costs and Benefits of High-Yield Farming." *Nature Sustainability* 1 (9): 9. https://doi.org/10.1038/s41893-018-0138-5.

Balmford, Andrew, Rhys Green, and Ben Phalan. 2015. "Land for Food & Land for Nature?" *Daedalus* 144 (4): 57–75. https://doi.org/10.1162/DAED_a_00354.

Barth, Miyabi, Jessica Zionts, Michelle Cain, and Myles R. Allen. 2023. *Agriculture Emissions and Warming in Aotearoa New Zealand to 2050: Insights from the Science*. Beef + Lamb NZ.

Bartlett, Harriet, Andrew Balmford, Mark A. Holmes, and James L. N. Wood. 2023. "Advancing the Quantitative Characterization of Farm Animal Welfare." *Proceedings of the Royal Society B: Biological Sciences* 290 (1995): 20230120. https://doi.org/10.1098/rspb.2023.0120.

Bartlett, Harriet, Márcia Zanella, Beatriz Kaori, et al. 2024. "Trade-Offs in the Externalities of Pig Production Are Not Inevitable." *Nature Food* 5 (4): 312–22. https://doi.org/10.1038/s43016-024-00921-2.

Bastianoni, Simone, Michela Marchi, Dario Caro, Paolo Casprini, and Federico Maria Pulselli. 2014. "The Connection between 2006 IPCC GHG Inventory Methodology and ISO 14064-1 Certification Standard – A Reference Point for the Environmental Policies at Sub-National Scale." *Environmental Science & Policy* 44 (December): 97–107. https://doi.org/10.1016/j.envsci.2014.07.015.

Bastin, Jean-Francois, Yelena Finegold, Claude Garcia, et al. 2019. "The Global Tree Restoration Potential." *Science* 365 (6448): 76–79. https://doi.org/10.1126/science.aax0848.

Beauchemin, Karen A., Emilio M. Ungerfeld, Adibe L. Abdalla, et al. 2022. "*Invited Review:* Current Enteric Methane Mitigation Options." *Journal of Dairy Science* 105 (12): 9297–326. https://doi.org/10.3168/jds.2022-22091.

BEIS (GOV.UK). 2022. "Agricultural Land Use in United Kingdom at 1 June 2022." https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom/agricultural-land-use-in-united-kingdom-at-1-june-2022.

BEIS. 2023. *2021 UK Greenhouse Gas Emissions, Final Figures*. Department for Business, Energy & Industrial Strategy.

Benton, Tim, C. Bieg, H. Harwatt, R. Pudasaini, and L. Wellesley. 2021. *Food System Impacts on Biodiversity Loss*. Energy, Environment and Resources Program, Chatham House.

Bhaskar, Roy. 1975. *A Realist Theory of Science*. Routledge.

Bhaskar, Roy. 1979. *The Possibility of Naturalism: A Philosophical Critique of the Contemporary Human Sciences*. Routledge.

Bihu, Reuben. 2024. *Qualitative Data Analysis: Novelty in Deductive and Inductive Coding*. https://www.authorea.com/users/717923/articles/705285-qualitative-data-analysis-novelty-in-deductive-and-inductive-coding.

Bishop, George, Colm Duffy, Rémi Prudhomme, et al. 2024. "Defining National Net Zero Goals Is Critical for Food and Land Use Policy." *Communications Earth & Environment* 5 (1): 104. https://doi.org/10.1038/s43247-024-01275-0.

Blackwell, Martin S. A., Taro Takahashi, Laura M. Cardenas, et al. 2024. "Potential Unintended Consequences of Agricultural Land Use Change Driven by Dietary Transitions." *Npj Sustainable Agriculture* 2 (1): 1. https://doi.org/10.1038/s44264-023-00008-8.

Blonk Consultants. 2013. *Direct Land Use Change Assessment Tool, Version 2013.1*. Released.

Blonk Consultants. 2022. "LUC Impact-Dataset." https://portal.blonksustainability.nl/tool/26/.

Boer, IJM de, C. Cederberg, S. Eady, et al. 2011. "Greenhouse Gas Mitigation in Animal Production: Towards an Integrated Life Cycle Sustainability Assessment." *Current Opinion in Environmental Sustainability*, Carbon and nitrogen cycles, vol. 3 (5): 423–31. https://doi.org/10.1016/j.cosust.2011.08.007.

Boezeman, Daan, David de Pue, Morten Graversgaard, and Stefan Möckel. 2023. "Less Livestock in North-Western Europe? Discourses and Drivers Behind Livestock Buyout Policies." *EuroChoices* 22 (2): 4–12. https://doi.org/10.1111/1746-692X.12399.

Boren, Zach (Unearthed). 2022. "How the Beef Industry Is Trying to Change the Maths of Climate Change." March 9. https://unearthed.greenpeace.org/2022/03/09/global-warming-potential-star-methane-agriculture-net-zero/.

Bromwich, Talitha, Thomas B. White, Alice Bouchez, et al. 2025. "Navigating Uncertainty in Life Cycle Assessment-Based Approaches to Biodiversity Footprinting." *Methods in Ecology and Evolution* n/a (n/a). https://doi.org/10.1111/2041-210X.70001.

Broom, Donald M. 2011. "Animal Welfare: Concepts, Study Methods and Indicators." *Revista Colombiana de Ciencias Pecuarias* 24 (3): 306–21.

Broom, Donald M. 2019. "Animal Welfare Complementing or Conflicting with Other Sustainability Issues." *Applied Animal Behaviour Science* 219 (October): 104829. https://doi.org/10.1016/j.applanim.2019.06.010.

Brown, P., L. M. Cardenas, S. Choudrie, et al. 2021. "UK Greenhouse Gas Inventory, 1990 to 2019: Annual Report for Submission under the Framework Convention on Climate Change." Department for Business, Energy & Industrial Strategy.

Browning, Heather. 2022. "The Measurability of Subjective Animal Welfare." Text. Imprint Academic, March. https://www.ingentaconnect.com/content/imp/jcs/2022/00000029/f0020003/art00007#.

Brownlie. 2023. "New Report Calls for Focus on Warming Impact of Gases, Not Total Emissions, to Reach Climate Goal." NZ. *Newshub*. https://www.newshub.co.nz/home/new-zealand/2023/09/new-report-calls-for-focus-on-warming-impact-of-gases-not-total-emissions-to-reach-climate-goal.html.

Brugha, Ruairí, and Zsuzsa Varvasovszky. 2000. “Stakeholder Analysis: A Review.” *Health Policy and Planning* 15 (3): 239–46. https://doi.org/10.1093/heapol/15.3.239.

BSI. 2012. “PAS 2050-1:2012. ‘Assessment of Life Cycle Greenhouse Gas Emissions from Horticultural Products. Supplementary Requirements for the Cradle to Gate Stages of GHG Assessments of Horticultural Products Undertaken in Accordance with PAS 2050’.” British Standards Institution, London.

Buck, Holly Jean, Wim Carton, Jens Friis Lund, and Nils Markusson. 2023. “Why Residual Emissions Matter Right Now.” *Nature Climate Change* 13 (4): 351–58. https://doi.org/10.1038/s41558-022-01592-2.

Burgess, P. J., and A. Graves. 2022. *The Potential Contribution of Agroforestry to Net Zero Objectives. Report for the Woodland Trust*. Cranfield University.

Burgess, PJ, J. Harris, and LK Deeks. 2019. *Regenerative Agriculture: Identifying the Impact; Enabling the Potential. Report for SYSTEMIQ*. Cranfield University.

Burton, Rob J. F. 2004. “Seeing Through the ‘Good Farmer’s’ Eyes: Towards Developing an Understanding of the Social Symbolic Value of ‘Productivist’ Behaviour.” *Sociologia Ruralis* 44 (2): 195–215. https://doi.org/10.1111/j.1467-9523.2004.00270.x.

Caffrey, Kevin R., and Matthew W. Veal. 2013. “Conducting an Agricultural Life Cycle Assessment: Challenges and Perspectives.” *The Scientific World Journal* 2013 (December): 472431. https://doi.org/10.1155/2013/472431.

Cain, Michelle, John Lynch, Myles R. Allen, Jan S. Fuglestvedt, David J. Frame, and Adrian H. Macey. 2019. “Improved Calculation of Warming-Equivalent Emissions for Short-Lived Climate Pollutants.” *Npj Climate and Atmospheric Science* 2 (1): 1. https://doi.org/10.1038/s41612-019-0086-4.

Cain, Michelle, Keith Shine, David Frame, et al. 2021. “Comment on ‘Unintentional Unfairness When Applying New Greenhouse Gas Emissions Metrics at Country Level.’” *Environmental Research Letters* 16 (6): 068001. https://doi.org/10.1088/1748-9326/ac02eb.

Campbell, Bruce M., Douglas J. Beare, Elena M. Bennett, et al. 2017. “Agriculture Production as a Major Driver of the Earth System Exceeding Planetary Boundaries.” *Ecology and Society* 22 (4). https://www.jstor.org/stable/26798991.

Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. “The Environmental Impact of Dairy Production: 1944 Compared with 20071.” *Journal of Animal Science* 87 (6): 2160–67. https://doi.org/10.2527/jas.2009-1781.

Carlile, Rachel, and Tara Garnett. 2021. “What Is Agroecology?” TABLE Explainer.

Carter, Nicholas, and Nusa Urbancic. 2023. *Seeing Stars: The New Metric That Could Allow the Meat and Dairy Industry to Avoid Climate Action*. Changing Markets Foundation.

Cartwright, Nancy, and Jeremy Hardie. 2012. *Evidence-Based Policy: A Practical Guide to Doing It Better*. Oxford University Press. https://doi.org/10.1093/acprof:osobl/9780199841608.001.0001.

Castle, Sarah E., Daniel C. Miller, Pablo J. Ordonez, Kathy Baylis, and Karl Hughes. 2021. "The Impacts of Agroforestry Interventions on Agricultural Productivity, Ecosystem Services, and Human Well-being in Low- and Middle-income Countries: A Systematic Review." *Campbell Systematic Reviews* 17 (2): e1167. https://doi.org/10.1002/cl2.1167.

CBS (How do we use our land? - The Netherlands in Numbers 2020 | CBS). 2020. "How do we use our land? - The Netherlands in Numbers 2020 | CBS." https://longreads.cbs.nl/the-netherlands-in-numbers-2020/how-do-we-use-our-land.

CBS (Statistics Netherlands). 2022. "Which Sectors Emit Greenhouse Gases?" https://www.cbs.nl/en-gb/dossier/greenhouse-gas-emissions/which-sectors-emit-greenhouse-gases-.

CCC. 2020. "Sixth Carbon Budget." *Climate Change Committee*. https://www.theccc.org.uk/publication/sixth-carbon-budget/.

CCC. 2025. *The Seventh Carbon Budget*. Climate Change Committee. https://www.theccc.org.uk/publication/the-seventh-carbon-budget/.

CE (Conservation Evidence). 2024. "Conservation Evidence - Site." https://www.conservationevidence.com/.

Chapman, Melissa, Martin Jung, David Leclère, et al. 2025. "Meeting European Union Biodiversity Targets under Future Land-Use Demands." *Nature Ecology & Evolution* 9 (5): 810–21. https://doi.org/10.1038/s41559-025-02671-1.

Chiarucci, Alessandro, Miguel B. Araújo, Guillaume Decocq, Carl Beierkuhnlein, and José María Fernández-Palacios. 2010. "The Concept of Potential Natural Vegetation: An Epitaph?" *Journal of Vegetation Science* 21 (6): 1172–78. https://doi.org/10.1111/j.1654-1103.2010.01218.x.

Clark, Michael A., Nina G. G. Domingo, Kimberly Colgan, et al. 2020. "Global Food System Emissions Could Preclude Achieving the 1.5° and 2°C Climate Change Targets." *Science* 370 (6517): 705–8. https://doi.org/10.1126/science.aba7357.

Clark, Michael A., Marco Springmann, Jason Hill, and David Tilman. 2019. "Multiple Health and Environmental Impacts of Foods." *Proceedings of the National Academy of Sciences* 116 (46): 23357–62. https://doi.org/10.1073/pnas.1906908116.

Clarke, Hannah (AHDB). 2024. "How Much Beef Is Produced from the GB Dairy Herd?" https://ahdb.org.uk/news/how-much-beef-is-produced-from-the-gb-dairy-herd.

Climate Change Committee. 2020. *The Sixth Carbon Budget: The UK's Path to Net Zero*.

Coghlan, David, and Mary Brydon-Miller. 2014. "Positionality." In *The SAGE Encyclopedia of Action Research*. SAGE Publications Ltd. https://doi.org/10.4135/9781446294406.

Collas, Lydia, and Dustin Benton. 2023a. *Farming for the Future: How Paying for Public Goods Can Create a Thriving Rural Economy*. Green Alliance.

Collas, Lydia, and Dustin Benton. 2023b. *Shaping UK Land Use: Priorities for Food, Nature and Climate*. Green Alliance.

Colomb, Vincent, Ophélie Touchemoulin, Louis Bockel, et al. 2013. "Selection of Appropriate Calculators for Landscape-Scale Greenhouse Gas Assessment for Agriculture and Forestry." *Environmental Research Letters* 8 (1): 015029. https://doi.org/10.1088/1748-9326/8/1/015029.

Commission Notice – Guidance Document for Regulation (EU) 2023/1115 on Deforestation-Free Products, COM, ENV (2025). http://data.europa.eu/eli/C/2025/4524/oj.

Correddu, Fabio, Mondina Francesca Lunesu, Maria Francesca Caratzu, and Giuseppe Pulina. 2023. "Recalculating the Global Warming Impact of Italian Livestock Methane Emissions with New Metrics." *Italian Journal of Animal Science*, December 31. World. https://www.tandfonline.com/doi/abs/10.1080/1828051X.2023.2167616.

Coulson, Helen, and Paul Milbourne. 2022. "Agriculture, Food and Land: Struggles for UK Post-Brexit Agri-Food Justice." *Geoforum* 131 (May): 126–35. https://doi.org/10.1016/j.geoforum.2022.03.007.

Cozim-Melges, Felipe, Raimon Ripoll-Bosch, G. F. (Ciska) Veen, et al. 2024. "Farming Practices to Enhance Biodiversity across Biomes: A Systematic Review." *Npj Biodiversity* 3 (1): 1. https://doi.org/10.1038/s44185-023-00034-2.

Crenna, Eleonora, Alexandra Marques, Alessandra La Notte, and Serenella Sala. 2020. "Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges." *Environmental Science & Technology* 54 (16): 9715–28. https://doi.org/10.1021/acs.est.9b05153.

Cressey, P. J., A. Gautam, A. J. Pearson, J. Fowles, P. Tyagi, and C. T. Eason. 2025. "Toxicology of Bromoform, a Natural Constituent of the Seaweed *Asparagopsis* Spp. Used to Inhibit Methanogenesis in Cattle, Suggests Negligible Risks to Humans." *Regulatory Toxicology and Pharmacology* 163 (December): 105937. https://doi.org/10.1016/j.yrtph.2025.105937.

Curran, Mary Ann. 2013. "Life Cycle Assessment: A Review of the Methodology and Its Application to Sustainability." *Current Opinion in Chemical Engineering*, Energy and environmental engineering / Reaction engineering and catalysis, vol. 2 (3): 273–77. https://doi.org/10.1016/j.coche.2013.02.002.

Curtis, Philip G., Christy M. Slay, Nancy L. Harris, Alexandra Tyukavina, and Matthew C. Hansen. 2018. "Classifying Drivers of Global Forest Loss." *Science* 361 (6407): 1108–11. https://doi.org/10.1126/science.aau3445.

Cusworth, George, Jeremy Brice, Jamie Lorimer, and Tara Garnett. 2023. "When You Wish upon a (GWP) Star: Environmental Governance and the Reflexive Performativity of Global Warming Metrics." *Social Studies of Science* 53 (1): 3–28. https://doi.org/10.1177/03063127221134275.

Cusworth, George, and Jennifer Dodsworth. 2021. "Using the 'Good Farmer' Concept to Explore Agricultural Attitudes to the Provision of Public Goods. A Case Study of Participants in an English Agri-Environment Scheme." *Agriculture and Human Values* 38 (4): 929–41. https://doi.org/10.1007/s10460-021-10215-z.

Cusworth, George, and Tara Garnett. 2023. *What Is Regenerative Agriculture?* TABLE. https://doi.org/10.56661/2d7b8d1c.

DairyNZ. 2023. "Kiwi Farmers Need Science-Led Methane Review." https://www.dairynz.co.nz/news/kiwi-farmers-need-science-led-methane-review/.

Damiani, Mattia, Taija Sinkko, Carla Caldeira, Davide Tosches, Marine Robuchon, and Serenella Sala. 2023. "Critical Review of Methods and Models for Biodiversity Impact Assessment and Their Applicability in the LCA Context." *Environmental Impact Assessment Review* 101 (July): 107134. https://doi.org/10.1016/j.eiar.2023.107134.

Danermark, Berth, Mats Ekström, and Jan Ch Karlsson. 2019. *Explaining Society: Critical Realism in the Social Sciences*. 2nd ed. Routledge. https://doi.org/10.4324/9781351017831.

De Bruijn, Hans, Robbert Van Duin, Mark A. J. Huijbregts, et al., eds. 2002. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*. Vol. 7. Eco-Efficiency in Industry and Science. Springer Netherlands. https://doi.org/10.1007/0-306-48055-7.

DEFRA (GOV.UK). 2013. "Farm Energy Use." August 16. https://www.gov.uk/government/statistics/farm-energy-use.

DEFRA. 2018. "A Green Future: Our 25 Year Plan to Improve the Environment." HM Government.

DEFRA. 2020. *The Path to Sustainable Farming: An Agricultural Transition Plan 2021 to 2024*. Department for Environment Food & Rural Affairs.

DEFRA (GOV.UK). 2021. "Chapter 7: Crops." https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2021/chapter-7-crops.

DEFRA. 2022. *National Statistics: Agriculture in the United Kingdom 2021*.

DEFRA (GOV.UK). 2023a. "Agricultural Land Use in the United Kingdom." December 14. https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom.

DEFRA. 2023b. *Environmental Land Management (ELM) Update: How Government Will Pay for Land-Based Environment and Climate Goods and Services*. Policy paper. Department for Environment Food & Rural Affairs. https://www.gov.uk/government/publications/environmental-land-management-update-how-government-will-pay-for-land-based-environment-and-climate-goods-and-services/environmental-land-management-elm-update-how-government-will-pay-for-land-based-environment-and-climate-goods-and-services#new-sfi-standards-for-2023.

DEFRA (GOV.UK). 2023c. "Livestock Populations in the United Kingdom." May 3. https://www.gov.uk/government/statistics/livestock-populations-in-the-united-kingdom.

DEFRA (GOV.UK). 2024a. "Agricultural Facts: Summary." https://www.gov.uk/government/statistics/agricultural-facts-england-regional-profiles/agricultural-facts-summary.

DEFRA (GOV.UK). 2024b. "Agricultural Land Use in United Kingdom at 1 June 2024." https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom/agricultural-land-use-in-united-kingdom-at-1-june-2023.

DEFRA. 2024c. *UK Food Security Report 2021, Updated 22 October 2024*. Defra.

DEFRA (GOV.UK). 2025a. "Agri-Climate Report 2024." https://www.gov.uk/government/statistics/agri-climate-report-2024/agri-climate-report-2024.

DEFRA. 2025b. "Agricultural Land Used to Feed Livestock in the United Kingdom." https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom.

DEFRA (GOV.UK). 2025c. "Sustainable Farming Incentive Action Uptake Data January 2025." https://www.gov.uk/government/statistics/sustainable-farming-incentive-action-uptake-data-january-2025/sustainable-farming-incentive-action-uptake-data-january-2025.

Del Prado, A., J. Lynch, S. Liu, B. Ridoutt, G. Pardo, and F. Mitloehner. 2023. "Animal Board Invited Review: Opportunities and Challenges in Using GWP* to Report the Impact of Ruminant Livestock on Global Temperature Change." *Animal: An International Journal of Animal Bioscience* 17 (5): 100790. https://doi.org/10.1016/j.animal.2023.100790.

Denmark Climate Act, Act. No 965 (2020).

Dijk, Michiel van, Tom Morley, Marie Luise Rau, and Yashar Saghai. 2021. "A Meta-Analysis of Projected Global Food Demand and Population at Risk of Hunger for the Period 2010–2050." *Nature Food* 2 (7): 494–501. https://doi.org/10.1038/s43016-021-00322-9.

Dillon, Jasmine A., Kim R. Stackhouse-Lawson, Greg J. Thoma, et al. 2021. “Current State of Enteric Methane and the Carbon Footprint of Beef and Dairy Cattle in the United States.” *Animal Frontiers* 11 (4): 57–68. https://doi.org/10.1093/af/vfab043.

DoAFM. 2022. *Food Vision 2030: A World Leader in Sustainable Food Systems*. Department of Agriculture, food and the Marine.

DoAFM. 2024. *Afforestation Scheme 2023-2027 Document*. Forestry Division, Department of Agriculture, Food and the Marine.

Doka, Gabor, William Hillier, Simo Kaila, et al. 2002. *The Assessment of Environmental Impacts Caused by Land Use in the Life Cycle Assessment of Forestry and Forest Products - Guidelines, Hints and Recommendations -*. COST.

Donnison, Caspar L., and Donal Murphy-Bokern. 2023. “Are Climate Neutrality Claims in the Livestock Sector Too Good to Be True?” *Environmental Research Letters* 19 (1): 011001. https://doi.org/10.1088/1748-9326/ad0f75.

Duffy, Colm, Carl Doedens, Róisín Moriarty, Hannah Daly, David Styles, and Malte Meinshausen. 2025. “National Temperature Neutrality, Agricultural Methane and Climate Policy: Reinforcing Inequality in the Global Food System.” *Environmental Research Letters* 20 (9): 094019. https://doi.org/10.1088/1748-9326/adf12d.

Dwyer, Janet, David R. Chadwick, Jessica Davies, et al. 2024. *NMEG Report: Improving Policy and Practice for Agricultural Nutrient Use and Management*. DEFRA.

Eardley, ByNick, Matt Murphy, Olga Robinson, and Marco SilvaBBC Verify (BBC News). 2024. “Why Misinformation about Cow Feed Additive Bovaer Prompted People to Throw Arla Milk Away.” December 3. https://www.bbc.co.uk/news/articles/c8rjdgre3vpo.

Eating Better. 2019. “Better by Half: A Roadmap to Less and Better Meat and Dairy.” https://www.eating-better.org/news-and-reports/reports/better-by-half-a-roadmap-to-less-and-better-meat-and-dairy/.

Edelenbosch, Oreane Y., Andries F. Hof, Maarten van den Berg, et al. 2024. “Reducing Sectoral Hard-to-Abate Emissions to Limit Reliance on Carbon Dioxide Removal.” *Nature Climate Change* 14 (7): 715–22. https://doi.org/10.1038/s41558-024-02025-y.

Edwards, Paul K., Joe O’Mahoney, and Steve Vincent, eds. 2014. *Studying Organizations Using Critical Realism: A Practical Guide*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199665525.001.0001.

Ellis, Erle C., Kees Klein Goldewijk, Stefan Siebert, Deborah Lightman, and Navin Ramankutty. 2010. “Anthropogenic Transformation of the Biomes, 1700 to 2000.” *Global Ecology and Biogeography* 19 (5): 589–606. https://doi.org/10.1111/j.1466-8238.2010.00540.x.

EPA (Environmental Protection Agency Ireland). 2025. “Agriculture.” https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/.

Erb, Karl-Heinz, Thomas Kastner, Christoph Plutzar, et al. 2018. “Unexpectedly Large Impact of Forest Management and Grazing on Global Vegetation Biomass.” *Nature* 553 (7686): 7686. https://doi.org/10.1038/nature25138.

European Commission (European Commission - European Commission). 2021. “Political Agreement on New Common Agricultural Policy.” Text. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_2711.

European Commission. 2022. “Progress on Climate Action - Country Profile: Denmark.” https://climate.ec.europa.eu/eu-action/climate-strategies-targets/progress-climate-action_en.

European Commission. 2024. “Carbon Removals and Carbon Farming - Climate Action - European Commission.” https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en.

European Commission. 2025a. “CAP at a Glance - European Commission.” October 24. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en.

European Commission. 2025b. “Deforestation Regulation Implementation - Green Forum - European Commission.” https://green-forum.ec.europa.eu/nature-and-biodiversity/deforestation-regulation-implementation_en.

European Commission. 2025c. *THE 28 CAP STRATEGIC PLANS UNDERWAY Summary of Implementation in 2023-2024 – Facts and Figures*. European Commission.

European Commission. 2026. “Carbon Border Adjustment Mechanism - Taxation and Customs Union.” https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

Fan, Jianling, Cuiying Liu, Jianan Xie, et al. 2022. “Life Cycle Assessment on Agricultural Production: A Mini Review on Methodology, Application, and Challenges.” *International Journal of Environmental Research and Public Health* 19 (16): 16. https://doi.org/10.3390/ijerph19169817.

Fankhauser, Sam. 2021. “What next on Net Zero?” *One Earth* 4 (11): 1520–22. https://doi.org/10.1016/j.oneear.2021.10.017.

Fankhauser, Sam, Stephen M. Smith, Myles Allen, et al. 2022. “The Meaning of Net Zero and How to Get It Right.” *Nature Climate Change* 12 (1): 1. https://doi.org/10.1038/s41558-021-01245-w.

FAO. 2020. *Global Forest Resources Assessment 2020*. FAO. https://doi.org/10.4060/ca9825en.

FAO. 2022. *Global Livestock Environmental Assessment Model (GLEAM): Version 3.0*.

FAO. 2023. *Pathways towards Lower Emissions A Global Assessment of the Greenhouse Gas Emissions and Mitigation Options from Livestock Agrifood Systems*.

FAOSTAT. 2023a. “FAOSTAT: Crops and Livestock Products.” https://www.fao.org/faostat/en/#data/QCL.

FAOSTAT. 2023b. “FAOSTAT: Detailed Trade Matrix.” https://www.fao.org/faostat/en/#data/TM.

FAOSTAT. n.d. “FAOSTAT: Fertilizers by Nutrient.” Accessed May 12, 2025. https://www.fao.org/faostat/en/#data/RFN.

Farm Animal Welfare Council. 2009. “Farm Animal Welfare in Great Britain: Past, Present and Future.” *General - Animal Welfare*, January 1. https://www.wellbeingintlstudiesrepository.org/aw_welfare_gen/21.

Fearnside, Philip M. 2002a. “Time Preference in Global Warming Calculations: A Proposal for a Unified Index.” *Ecological Economics* 41 (1): 21–31. https://doi.org/10.1016/S0921-8009(02)00004-6.

Fearnside, Philip M. 2002b. “Why a 100-Year Time Horizon Should Be Used for GlobalWarming Mitigation Calculations.” *Mitigation and Adaptation Strategies for Global Change* 7 (1): 19–30. https://doi.org/10.1023/A:1015885027530.

Finch, Tom, Richard B. Bradbury, Tom Bradfer-Lawrence, et al. 2023. “Spatially Targeted Nature-Based Solutions Can Mitigate Climate Change and Nature Loss but Require a Systems Approach.” *One Earth* 6 (10): 1350–74. https://doi.org/10.1016/j.oneear.2023.09.005.

Fischer, Joern, Berry Brosi, Gretchen C. Daily, et al. 2008. “Should Agricultural Policies Encourage Land Sparing or Wildlife-Friendly Farming?” *Frontiers in Ecology and the Environment* 6 (7): 380–85. https://doi.org/10.1890/070019.

Foley, Jonathan A., Navin Ramankutty, Kate A. Brauman, et al. 2011. “Solutions for a Cultivated Planet.” *Nature* 478 (7369): 337–42. https://doi.org/10.1038/nature10452.

FOLU. 2023. *Aligning Regenerative Agricultural Practices with Outcomes to Deliver for People, Nature and Climate*. The Food and Land Use Coalition.

Forest Research. 2016. “Ecological Site Classification (ESC), Version 4.” https://www.forestresearch.gov.uk/tools-and-resources/fthr/ecological-site-classification/.

Fraser, David, Ian J. H. Duncan, Sandra A. Edwards, et al. 2013. “General Principles for the Welfare of Animals in Production Systems: The Underlying Science and Its Application.” *The Veterinary Journal* 198 (1): 19–27. https://doi.org/10.1016/j.tvjl.2013.06.028.

Freeman, R. Edward. 2010. *Strategic Management: A Stakeholder Approach*. Cambridge University Press. https://doi.org/10.1017/CBO9781139192675.

Fripp, Emily, Jonathan Gorman, Tina Schneider, et al. 2023. "Traceability and Transparency in Supply Chains for Agricultural and Forest Commodities." *World Resources Institute*, ahead of print, October. https://doi.org/10.46830/wrirpt.22.00156.

Fryer, Tom. 2022. "A Critical Realist Approach to Thematic Analysis: Producing Causal Explanations." *Journal of Critical Realism* 21 (4): 365–84. https://doi.org/10.1080/14767430.2022.2076776.

Fuglestvedt, J., J. Rogelj, R. J. Millar, et al. 2018. "Implications of Possible Interpretations of 'Greenhouse Gas Balance' in the Paris Agreement." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376 (2119): 20160445. https://doi.org/10.1098/rsta.2016.0445.

Fuglestvedt, Jan S., Terje K. Berntsen, Odd Godal, Robert Sausen, Keith P. Shine, and Tora Skodvin. 2003. "Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices." *Climatic Change* 58 (3): 267–331. https://doi.org/10.1023/A:1023905326842.

Fuglestvedt, J.S. 2000. "Climate Implications of GWP-Based Reductions in Greenhouse Gas Emissions." *Geophysical Research Letters* 27 (3): 409–12.

Galletta, Anne, and William E. Cross, eds. 2013. *Mastering the Semi-Structured Interview and beyond: From Research Design to Analysis and Publication*. Qualitative Studies in Psychology. New York University Press.

Gao, Tao, Qing Liu, and Jianping Wang. 2014. "A Comparative Study of Carbon Footprint and Assessment Standards." *International Journal of Low-Carbon Technologies* 9 (3): 237–43. https://doi.org/10.1093/ijlct/ctt041.

Garnett, Tara, Cécile Godde, A. Muller, et al. 2017. *Grazed and Confused?: Ruminating on Cattle, Grazing Systems, Methane, Nitrous Oxide, the Soil Carbon Sequestration Question - and What It All Means for Greenhouse Gas Emissions*. https://research.wur.nl/en/publications/grazed-and-confused-ruminating-on-cattle-grazing-systems-methane-.

Garrett, R. D., S. Levy, K. M. Carlson, et al. 2019. "Criteria for Effective Zero-Deforestation Commitments." *Global Environmental Change* 54 (January): 135–47. https://doi.org/10.1016/j.gloenvcha.2018.11.003.

Garvey, Alice, Jonathan B. Norman, Anne Owen, and John Barrett. 2021. "Towards Net Zero Nutrition: The Contribution of Demand-Side Change to Mitigating UK Food Emissions." *Journal of Cleaner Production* 290 (March): 125672. https://doi.org/10.1016/j.jclepro.2020.125672.

Gerlagh, Reyer, and Bob van der Zwaan. 2004. "A Sensitivity Analysis of Timing and Costs of Greenhouse Gas Emission Reductions." *Climatic Change* 65 (1): 39–71. https://doi.org/10.1023/B:CLIM.0000037497.49722.c5.

Gerten, Dieter, Vera Heck, Jonas Jägermeyr, et al. 2020. "Feeding Ten Billion People Is Possible within Four Terrestrial Planetary Boundaries." *Nature Sustainability* 3 (3): 200–208. https://doi.org/10.1038/s41893-019-0465-1.

Glasson, Christopher R. K., Robert D. Kinley, Rocky de Nys, et al. 2022. "Benefits and Risks of Including the Bromoform Containing Seaweed *Asparagopsis* in Feed for the Reduction of Methane Production from Ruminants." *Algal Research* 64 (May): 102673. https://doi.org/10.1016/j.algal.2022.102673.

Godfray, H. Charles J., Paul Aveyard, Tara Garnett, et al. 2018. "Meat Consumption, Health, and the Environment." *Science* 361 (6399): eaam5324. https://doi.org/10.1126/science.aam5324.

Godfray, H. Charles J., John R. Beddington, Ian R. Crute, et al. 2010. "Food Security: The Challenge of Feeding 9 Billion People." *Science* 327 (5967): 812–18. https://doi.org/10.1126/science.1185383.

Goldman, Elizabeth, and Mikaela Weisse. 2024. "Deforestation Linked to Agriculture | Global Forest Review." https://gfr.wri.org/forest-extent-indicators/deforestation-agriculture.

Government of Ireland. 2025. *Climate Action Plan 2025*. Government of Ireland.

Green, Jessica F., and Raúl Salas Reyes. 2023. "The History of Net Zero: Can We Move from Concepts to Practice?" *Climate Policy* 23 (7): 901–15. https://doi.org/10.1080/14693062.2023.2218334.

Green, Rhys E., Stephen J. Cornell, Jörn P. W. Scharlemann, and Andrew Balmford. 2005. "Farming and the Fate of Wild Nature." *Science* 307 (5709): 550–55. https://doi.org/10.1126/science.1106049.

Greenfield, Patrick. 2023. "Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Certifier Are Worthless, Analysis Shows." Environment. *The Guardian*, January 18. https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, et al. 2017. "Natural Climate Solutions." *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. https://doi.org/10.1073/pnas.1710465114.

Guba, Egon G., and Yvonna S. Lincoln. 2005. "Paradigmatic Controversies, Contradictions, and Emerging Confluences." In *The Sage Handbook of Qualitative Research, 3rd Ed*. Sage Publications Ltd.

Haas, Guido, Frank Wetterich, and Uwe Geier. 2000. “Life Cycle Assessment Framework in Agriculture on the Farm Level.” *The International Journal of Life Cycle Assessment* 5 (6): 345–48. https://doi.org/10.1007/BF02978669.

Haas, Y. de, R. F. Veerkamp, G. de Jong, and M. N. Aldridge. 2021. “Selective Breeding as a Mitigation Tool for Methane Emissions from Dairy Cattle.” *Animal*, Sustainable livestock systems for high-producing animals, vol. 15 (December): 100294. https://doi.org/10.1016/j.animal.2021.100294.

Haberl, Helmut, K. Heinz Erb, Fridolin Krausmann, et al. 2007. “Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth’s Terrestrial Ecosystems.” *Proceedings of the National Academy of Sciences* 104 (31): 12942–47. https://doi.org/10.1073/pnas.0704243104.

Hale, Thomas, Smith ,Stephen M., Black ,Richard, et al. 2022. “Assessing the Rapidly-Emerging Landscape of Net Zero Targets.” *Climate Policy* 22 (1): 18–29. https://doi.org/10.1080/14693062.2021.2013155.

Hale, Thomas, Thom Wetzer, Selam Kidane Abebe, et al. 2024. “Turning a Groundswell of Climate Action into Ground Rules for Net Zero.” *Nature Climate Change* 14 (4): 306–8. https://doi.org/10.1038/s41558-024-01967-7.

Hanson, Craig, and Janet Ranganathan. 2022. *How to Manage the Global Land Squeeze? Produce, Protect, Reduce, Restore*. February 14. https://www.wri.org/insights/manage-global-land-squeeze-produce-protect-reduce-restore.

Harvey, L. D. D. 1993. “A Guide to Global Warming Potentials (GWPs).” *Energy Policy*.

Hayek, Matthew N., and Rachael D. Garrett. 2018. “Nationwide Shift to Grass-Fed Beef Requires Larger Cattle Population.” *Environmental Research Letters* 13 (8): 084005. https://doi.org/10.1088/1748-9326/aad401.

Hayek, Matthew N., Helen Harwatt, William J. Ripple, and Nathaniel D. Mueller. 2021. “The Carbon Opportunity Cost of Animal-Sourced Food Production on Land.” *Nature Sustainability* 4 (1): 1. https://doi.org/10.1038/s41893-020-00603-4.

Hayek, Matthew N., Johannes Piipponen, Matti Kummu, Kajsa Resare Sahlin, Shelby C. McClelland, and Kimberly Carlson. 2024. “Opportunities for Carbon Sequestration from Removing or Intensifying Pasture-Based Beef Production.” *Proceedings of the National Academy of Sciences* 121 (46): e2405758121. https://doi.org/10.1073/pnas.2405758121.

Heinke, Jens, Mats Lannerstad, Dieter Gerten, et al. 2020. “Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity.” *Water Resources Research* 56 (12): e2019WR026995. https://doi.org/10.1029/2019WR026995.

Hellweg, Stefanie, and Llorenç Milà i Canals. 2014. “Emerging Approaches, Challenges and Opportunities in Life Cycle Assessment.” *Science* 344 (6188): 1109–13. https://doi.org/10.1126/science.1248361.

Herr, Kathryn, and Gary L.Anderson. 2005. *The Action Research Dissertation: A Guide for Students and Faculty*. SAGE Publications, Inc. https://doi.org/10.4135/9781452226644.

Herrero, Mario, Petr Havlík, Hugo Valin, et al. 2013. "Biomass Use, Production, Feed Efficiencies, and Greenhouse Gas Emissions from Global Livestock Systems." *Proceedings of the National Academy of Sciences of the United States of America* 110 (52): 20888–93.

Herrero, Mario, Benjamin Henderson, Petr Havlík, et al. 2016. "Greenhouse Gas Mitigation Potentials in the Livestock Sector." *Nature Climate Change* 6 (5): 452–61. https://doi.org/10.1038/nclimate2925.

Herzon, Irina, Rachel Mazac, Maijaliisa Erkkola, et al. 2024. "Both Downsizing and Improvements to Livestock Systems Are Needed to Stay within Planetary Boundaries." *Nature Food* 5 (8): 642–45. https://doi.org/10.1038/s43016-024-01030-w.

Hill, J. M., and M. Weulen Kranenbarg. 2025. "Polluted Nature, Polluted Debate: A Longitudinal Analysis of Disinformation Around the Nitrogen Crisis in The Netherlands." *European Journal on Criminal Policy and Research*, May 24, 1–25. https://doi.org/10.1007/s10610-025-09624-1.

Hobbs, Peter R., Ken Sayre, and Raj Gupta. 2008. "The Role of Conservation Agriculture in Sustainable Agriculture." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1491): 543–55. https://doi.org/10.1098/rstb.2007.2169.

Holl, Karen D., and Pedro H. S. Brancalion. 2020. "Tree Planting Is Not a Simple Solution." *Science* 368 (6491): 580–81. https://doi.org/10.1126/science.aba8232.

Houghton, John Theodore, ed. 2001. *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Chapter 6: Radiative Forcing of Climate Change. Cambridge University Press.

Houghton, R. A. 1991. "Tropical Deforestation and Atmospheric Carbon Dioxide." *Climatic Change* 19 (1): 99–118. https://doi.org/10.1007/BF00142217.

Hummel, Katrin, and Dominik Jobst. 2024. "An Overview of Corporate Sustainability Reporting Legislation in the European Union." *Accounting in Europe* 21 (3): 320–55. https://doi.org/10.1080/17449480.2024.2312145.

Huss, William R. 1988. "A Move toward Scenario Analysis." *International Journal of Forecasting*, Special Issue on: The Future of Forecasting, vol. 4 (3): 377–88. https://doi.org/10.1016/0169-2070(88)90105-7.

IGSD. 2024. "A Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030." Institute for Governance & Sustainable Development.

IPBES. 2019. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (Eds.).* IPBES Secretariat.

IPCC. 1990. "Climate Change: The IPCC Scientific Assessment (First Assessment Report)."

IPCC. 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 5: Land-Use Change & Forestry*.

IPCC. 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry /The Intergovernmental Panel on Climate Change. Ed. by Jim Penman*. Edited by Jim Penman. With IPPC National Greenhouse Gas Inventories Programme. Hayama, Kanagawa.

IPCC, ed. 2007. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC. 2014. *Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]*. IPCC.

IPCC. 2018. *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157940.

IPCC. 2019. "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S." IPCC, Switzerland.

IPCC. 2021a. *Annex VII: Glossary [Matthews, J.B.R., V. Möller, R. van Diemen, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, A. Reisinger (Eds.)]. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.)]. Cambridge University*

Press, Cambridge, United Kingdom and New York, NY, USA, Pp. 2215–2256. 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157896.

IPCC. 2021b. "Chapter 7: The Earth's Energy Budget, Climate Feedback, and Climate Sensitivity. In V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, & and B. Z. O. Yelekçi, R. Yu (Eds.),." *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

IPCC. 2021c. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.)]*. Cambridge University Press.

IPCC, IPCC, and UNEP, eds. 2005. *IPCC/TEAP Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons; Summary for Policymakers and Technical Summary*.

ISO. 2020. *ISO 22095:2020(En), Chain of Custody — General Terminology and Models*. 1st ed. https://www.iso.org/obp/ui/en/#iso:std:iso:22095:ed-1:v1:en.

ITA (International Trade Administration). 2024. "Ireland - Agricultural Sector." January 25. https://www.trade.gov/country-commercial-guides/ireland-agricultural-sector.

Jebari, Asma, Taro Takahashi, Michael R. F. Lee, et al. 2025. "Carbon Footprints of Greenhouse Gas Mitigation Measures for a Grass-Based Beef Cattle Finishing System in the UK." *The International Journal of Life Cycle Assessment* 30 (4): 654–67. https://doi.org/10.1007/s11367-025-02428-9.

Jenkins, S., R. J. Millar, N. Leach, and M. R. Allen. 2018. "Framing Climate Goals in Terms of Cumulative CO_2 -Forcing-Equivalent Emissions." *Geophysical Research Letters* 45 (6): 2795–804. https://doi.org/10.1002/2017GL076173.

Jia, Jimmy, Kaya Axelsson, Abrar Chaudhury, and Evan Taylor. 2023. "A Rapid Review of GHG Accounting Standards." *SSRN Electronic Journal*, ahead of print. https://doi.org/10.2139/ssrn.4523132.

Jia, Jimmy Yi-Jie. 2020. *The Corporate Energy Strategist's Handbook: Frameworks to Achieve Environmental Sustainability and Competitive Advantage*. Springer International Publishing AG.

Johnson, Justin Andrew, Carlisle Ford Runge, Benjamin Senauer, Jonathan Foley, and Stephen Polasky. 2014. "Global Agriculture and Carbon Trade-Offs." *Proceedings of the National Academy of Sciences* 111 (34): 12342–47. https://doi.org/10.1073/pnas.1412835111.

Jones, Sarah K., Andrea C. Sánchez, Damien Beillouin, et al. 2023. "Achieving Win-Win Outcomes for Biodiversity and Yield through Diversified Farming." *Basic and Applied Ecology* 67 (March): 14–31. https://doi.org/10.1016/j.baae.2022.12.005.

Joos, F., R. Roth, J. S. Fuglestvedt, et al. 2013. "Carbon Dioxide and Climate Impulse Response Functions for the Computation of Greenhouse Gas Metrics: A Multi-Model Analysis." *Atmospheric Chemistry and Physics* 13 (5): 2793–825. https://doi.org/10.5194/acp-13-2793-2013.

Kaushik, Vibha, and Christine A. Walsh. 2019. "Pragmatism as a Research Paradigm and Its Implications for Social Work Research." *Social Sciences* 8 (9): 9. https://doi.org/10.3390/socsci8090255.

Kebreab, Ermias, André Bannink, Eleanor May Pressman, et al. 2023. "A Meta-Analysis of Effects of 3-Nitrooxypropanol on Methane Production, Yield, and Intensity in Dairy Cattle." *Journal of Dairy Science* 106 (2): 927–36. https://doi.org/10.3168/jds.2022-22211.

Kebreab, Ermias, Anders Strathe, James Fadel, Luis Moraes, and James France. 2010. "Impact of Dietary Manipulation on Nutrient Flows and Greenhouse Gas Emissions in Cattle." *Revista Brasileira de Zootecnia* 39: 458–64. https://doi.org/https://doi.org/10.1590/S1516-35982010001300050.

Kirschbaum, Miko U. F., Annette L. Cowie, Josep Peñuelas, et al. 2024. "Is Tree Planting an Effective Strategy for Climate Change Mitigation?" *Science of The Total Environment* 909 (January): 168479. https://doi.org/10.1016/j.scitotenv.2023.168479.

Koellner, Thomas, Laura de Baan, Tabea Beck, et al. 2013. "UNEP-SETAC Guideline on Global Land Use Impact Assessment on Biodiversity and Ecosystem Services in LCA." *The International Journal of Life Cycle Assessment* 18 (6): 1188–202. https://doi.org/10.1007/s11367-013-0579-z.

Kopsieker, L., G. Costa Domingo, and E. Underwood. 2021. *Climate Mitigation Potential of Large-Scale Restoration in Europe. Analysis of the Climate Mitigation Potential of Restoring Habitats Listed in Annex I of the Habitats Directive*. Institute for European Environmental Policy.

KPMG and IDH. 2017. *Soy Reporting Initiative*.

Kuyah, Shem, Cory W. Whitney, Mattias Jonsson, et al. 2019. "Agroforestry Delivers a Win-Win Solution for Ecosystem Services in Sub-Saharan Africa. A Meta-Analysis." *Agronomy for Sustainable Development* 39 (5): 47. https://doi.org/10.1007/s13593-019-0589-8.

Lam, Wan Yee, Julia Chatterton, Sarah Sim, Michal Kulak, Angelica Mendoza Beltran, and Mark A. J. Huijbregts. 2021. "Estimating Greenhouse Gas Emissions from Direct Land Use Change Due to Crop Production in Multiple Countries." *Science of The Total Environment* 755 (February): 143338. https://doi.org/10.1016/j.scitotenv.2020.143338.

Lambin, Eric F., Holly K. Gibbs, Robert Heilmayr, et al. 2018. “The Role of Supply-Chain Initiatives in Reducing Deforestation.” *Nature Climate Change* 8 (2): 109–16. https://doi.org/10.1038/s41558-017-0061-1.

Landworkers’ Alliance, Pasture for Life, Sustain, and Hodmedod. 2023. *Soy No More: Breaking Away from Soy in UK Pig and Poultry Farming*.

Lang, John, Camilla Hyslop, Zhi Yi Yeo, et al. 2023. “Net Zero Tracker.” *Energy and Climate Intelligence Unit, Data-Driven EnviroLab, New Climate Institute, Oxford Net Zero*.

Lanzoni, L., L. Whatford, A. S. Atzori, et al. 2023. “Review: The Challenge to Integrate Animal Welfare Indicators into the Life Cycle Assessment.” *Animal* 17 (5): 100794. https://doi.org/10.1016/j.animal.2023.100794.

Lashof, Daniel A., and Dilip R. Ahuja. 1990. “Relative Contributions of Greenhouse Gas Emissions to Global Warming.” *Nature* 344 (6266): 6266. https://doi.org/10.1038/344529a0.

Leach, Nicholas J., Stuart Jenkins, Zebedee Nicholls, et al. 2021. “FaIRv2.0.0: A Generalized Impulse Response Model for Climate Uncertainty and Future Scenario Exploration.” *Geoscientific Model Development* 14 (5): 3007–36. https://doi.org/10.5194/gmd-14-3007-2021.

Legesse, G., K. H. Ominski, K. A. Beauchemin, et al. 2017. “BOARD-INVITED REVIEW: Quantifying Water Use in Ruminant Production1.” *Journal of Animal Science* 95 (5): 2001–18. https://doi.org/10.2527/jas.2017.1439.

Lehtilä, Anniina, and Ilkka Leinonen. 2025. “Carbon Opportunity Cost Approach May Result in Double Counting in Environmental Footprinting.” *The International Journal of Life Cycle Assessment* 30 (7): 1579–83. https://doi.org/10.1007/s11367-025-02475-2.

Li, Yanxian, Pan He, Yuli Shan, et al. 2024. “Reducing Climate Change Impacts from the Global Food System through Diet Shifts.” *Nature Climate Change* 14 (9): 943–53. https://doi.org/10.1038/s41558-024-02084-1.

Littell, Julia H., Jacqueline Corcoran, and Vijayan Pillai. 2008. *Systematic Reviews and Meta-Analysis*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195326543.001.0001.

Little, Ruth, Judith Tsouvalis, José Luis Fajardo Escoffié, Susan E. Hartley, and David Christian Rose. 2024. “Ideals and Practicalities of Policy Co-Design – Developing England’s Post-Brexit Environmental Land Management (ELM) Schemes.” *Land Use Policy* 147 (December): 107343. https://doi.org/10.1016/j.landusepol.2024.107343.

Liu, Shule, Joe Proudman, and Frank M. Mitloehner. 2021a. “Rethinking Methane from Animal Agriculture.” *CABI Agriculture and Bioscience* 2 (1): 22. https://doi.org/10.1186/s43170-021-00041-y.

Liu, Shule, Joe Proudman, and Frank M. Mitloehner. 2021b. "Rethinking Methane from Animal Agriculture." *CABI Agriculture and Bioscience* 2 (1): 22. https://doi.org/10.1186/s43170-021-00041-y.

Loconto, Allison, Marion Desquilbet, Théo Moreau, Denis Couvet, and Bruno Dorin. 2020. "The Land Sparing – Land Sharing Controversy: Tracing the Politics of Knowledge." *Land Use Policy* 96 (July): 103610. https://doi.org/10.1016/j.landusepol.2018.09.014.

Lord, N. S., A. Ridgwell, M. C. Thorne, and D. J. Lunt. 2016. "An Impulse Response Function for the 'Long Tail' of Excess Atmospheric CO_2 in an Earth System Model." *Global Biogeochemical Cycles* 30 (1): 2–17. https://doi.org/10.1002/2014GB005074.

Luedeling, Eike, Jan Börner, Wulf Amelung, Katja Schiffers, Keith Shepherd, and Todd Rosenstock. 2019. "Forest Restoration: Overlooked Constraints." *Science* 366 (6463): 315–315. https://doi.org/10.1126/science.aay7988.

Lynch, John, Michelle Cain, David Frame, and Raymond Pierrehumbert. 2021. "Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2-Emitting Sectors." *Frontiers in Sustainable Food Systems* 4 (February). https://doi.org/10.3389/fsufs.2020.518039.

Lynch, John, Michelle Cain, Raymond Pierrehumbert, and Myles Allen. 2020. "Demonstrating GWP*: A Means of Reporting Warming-Equivalent Emissions That Captures the Contrasting Impacts of Short- and Long-Lived Climate Pollutants." *Environmental Research Letters* 15 (4): 044023. https://doi.org/10.1088/1748-9326/ab6d7e.

Lynch, John, and Tara Garnett. 2021. "Policy to Reduce Greenhouse Gas Emissions: Is Agricultural Methane a Special Case?" *EuroChoices* 20 (2): 11–17. https://doi.org/10.1111/1746-692X.12317.

Lynch, John, and Raymond Pierrehumbert. 2024. "Does 'Net Zero' Mean Zero Cows?" *Bulletin of the Atomic Scientists* 80 (3): 153–57. https://doi.org/10.1080/00963402.2024.2339068.

Macedo, Marcia N., Ruth S. DeFries, Douglas C. Morton, Claudia M. Stickler, Gillian L. Galford, and Yosio E. Shimabukuro. 2012. "Decoupling of Deforestation and Soy Production in the Southern Amazon during the Late 2000s." *Proceedings of the National Academy of Sciences of the United States of America* 109 (4): 1341–46.

Maciel, Vinícius Gonçalves, Renan Milagres L. Novaes, Miguel Brandão, et al. 2022. "Towards a Non-Ambiguous View of the Amortization Period for Quantifying Direct Land-Use Change in LCA." *The International Journal of Life Cycle Assessment* 27 (12): 1299–315. https://doi.org/10.1007/s11367-022-02103-3.

Main, D. C. J., S. Mullan, C. Atkinson, M. Cooper, J. H. M. Wrathall, and H. J. Blokhuis. 2014. "Best Practice Framework for Animal Welfare Certification Schemes." *Trends in Food Science & Technology* 37 (2): 127–36. https://doi.org/10.1016/j.tifs.2014.03.009.

Mallapragada, Dharik S., and Bryan K. Mignone. 2020. "A Theoretical Basis for the Equivalence between Physical and Economic Climate Metrics and Implications for the Choice of Global Warming Potential Time Horizon." *Climatic Change* 158 (2): 107–24. https://doi.org/10.1007/s10584-019-02486-7.

Manne, Alan, and Richard Richels. 2006. "The Role of Non-CO_3 Greenhouse Gases and Carbon Sinks in Meeting Climate Objectives." *The Energy Journal* 27 (Special Issue: Multi-Greenhouse Gas Mitigation and Climate Policy).

Maron, Martine, Amrei von Hase, Fabien Quétier, Laura J. Sonter, Sebastian Theis, and Sophus O. S. E. zu Ermgassen. 2025. "Biodiversity Offsets, Their Effectiveness and Their Role in a Nature Positive Future." *Nature Reviews Biodiversity* 1 (3): 183–96. https://doi.org/10.1038/s44358-025-00023-2.

Mason, G., and M. Mendl. 1993. "Why Is There No Simple Way of Measuring AnimalWelfare?" *Animal Welfare* 2 (4): 301–19. https://doi.org/10.1017/S0962728600016092.

Maxwell, Joseph A. 2023. "A Realist Approach for Mixed Methods Research." In *Philosophical Foundations of Mixed Methods Research*. Routledge.

McAuliffe, Graham A., John Lynch, Michelle Cain, et al. 2023. "Are Single Global Warming Potential Impact Assessments Adequate for Carbon Footprints of Agri-Food Systems?" *Environmental Research Letters* 18 (8): 084014. https://doi.org/10.1088/1748-9326/ace204.

McAuliffe, Graham A., Taro Takahashi, and Michael R. F. Lee. 2018. "Framework for Life Cycle Assessment of Livestock Production Systems to Account for the Nutritional Quality of Final Products." *Food and Energy Security* 7 (3): e00143. https://doi.org/10.1002/fes3.143.

McCabe, C. J., H. M. Mashad, and F. M. Mitloehner. 2023. "The Path to Climate Neutrality for California Dairies." *CABI Reviews*, May 2, cabireviews.2023.0015. https://doi.org/10.1079/cabireviews.2023.0015.

McKenna, P., and S. Banwart. 2024. "Reassessing the Warming Impact of Methane Emissions from Irish Livestock Using GWP*: Historical Trends and Sustainable Futures." *Irish Journal of Agricultural and Food Research* 62 (January): 96–107. https://doi.org/10.15212/ijafr-2023-0107.

McLaughlin, Alison, and Pierre Mineau. 1995. "The Impact of Agricultural Practices on Biodiversity." *Agriculture, Ecosystems & Environment* 55 (3): 201–12. https://doi.org/10.1016/0167-8809(95)00609-V.

McNicol, Louise C., Non G. Williams, Dave Chadwick, et al. 2024. "Net Zero Requires Ambitious Greenhouse Gas Emission Reductions on Beef and Sheep Farms Coordinated with Afforestation and Other Land Use Change Measures." *Agricultural Systems* 215 (March): 103852. https://doi.org/10.1016/j.agsy.2024.103852.

Meinshausen, Malte, and Zebedee Nicholls. 2022. “GWP*is a Model, Not a Metric.” *Environmental Research Letters* 17 (4): 041002. https://doi.org/10.1088/1748-9326/ac5930.

Messé, Arnaud, Claus C. Hilgetag, and Marc-Thorsten Hütt. 2025. “Simple Rules for Simple Models.” *Physics of Life Reviews* 55 (December): 217–28. https://doi.org/10.1016/j.plrev.2025.10.006.

Milà i Canals, Llorenç, Christian Bauer, Jochen Depestele, et al. 2007. “Key Elements in a Framework for Land Use Impact Assessment Within LCA (11 Pp).” *The International Journal of Life Cycle Assessment* 12 (1): 5–15. https://doi.org/10.1065/lca2006.05.250.

Milford, Anna Birgitte, Chantal Le Mouël, Benjamin Leon Bodirsky, and Susanne Rolinski. 2019. “Drivers of Meat Consumption.” *Appetite* 141 (October): 104313. https://doi.org/10.1016/j.appet.2019.06.005.

Minasny, Budiman, Brendan P. Malone, Alex B. McBratney, et al. 2017. “Soil Carbon 4 per Mille.” *Geoderma* 292 (April): 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Ministry for the Green Tripartite. 2024. “Aftale Om et Grønt Danmark.” Landbrug & Fødevarer, Danmarks Naturfredningsforening, Fødevareforbundet NNF, Dansk Metal, Dansk Industri og Kommunernes Landsforening.

Mitloehner, Frank, Ermias Kebreab, and Michael Boccadoro. 2020. *Methane, Cows, and Climate Change: California Dairy’s Path to Climate Neutrality*. UC Davis CLEAR Center.

Mohankumar Sajeev, Erangu Purath, Wilfried Winiwarter, and Barbara Amon. 2018. “Greenhouse Gas and Ammonia Emissions from Different Stages of Liquid Manure Management Chains: Abatement Options and Emission Interactions.” *Journal of Environmental Quality* 47 (1): 30–41. https://doi.org/10.2134/jeq2017.05.0199.

Morelli, Ben, Troy R. Hawkins, Briana Niblick, et al. 2018. “Critical Review of Eutrophication Models for Life Cycle Assessment.” *Environmental Science & Technology* 52 (17): 9562–78. https://doi.org/10.1021/acs.est.8b00967.

Morgan, David L. 2007. “Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods.” *Journal of Mixed Methods Research* 1 (1): 48–76. https://doi.org/10.1177/2345678906292462.

Morgan, David L. 2014. *Integrating Qualitative and Quantitative Methods: A Pragmatic Approach*. SAGE.

Moss, Richard H., Jae A. Edmonds, Kathy A. Hibbard, et al. 2010. “The next Generation of Scenarios for Climate Change Research and Assessment.” *Nature* 463 (7282): 747–56. https://doi.org/10.1038/nature08823.

Mukherji, Aditi, Claudia Arndt, Jacobo Arango, et al. 2023. *Achieving Agricultural Breakthrough: A Deep Dive into Seven Technological Areas*. September 14. https://hdl.handle.net/10568/131852.

Muller, Adrian. 2018. "Comment on Searchinger et al. 2018." *Forschungsinstitut Für Biologischen Landbau FiBL*.

Muller, Adrian, Christian Schader, Nadia El-Hage Scialabba, et al. 2017. "Strategies for Feeding the World More Sustainably with Organic Agriculture." *Nature Communications* 8 (1): 1. https://doi.org/10.1038/s41467-017-01410-w.

Müller-Wenk, Ruedi, and Miguel Brandão. 2010. "Climatic Impact of Land Use in LCA—Carbon Transfers between Vegetation/Soil and Air." *The International Journal of Life Cycle Assessment* 15 (2): 172–82. https://doi.org/10.1007/s11367-009-0144-y.

Myhre, G., D. Shindell, F. M. Breon, et al. 2013. *Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

National Food Strategy. 2021. *National Food Strategy: Independent Review, The Plan*.

Nemecek, T., X. Bengoa, J. Lansche, et al. 2019. *Methodological Guidelines for the Life Cycle Inventory of Agricultural Products. Version 3.5*. World Food LCA Database (WFLDB). Quantis and Agroscope.

Net Zero Tracker. 2023. *Net Zero Stocktake 2023*. NewClimate Institute, Oxford Net Zero, Energy and Climate Intelligence Unit and Data-Driven EnviroLab.

Net Zero Tracker. 2025. *Net Zero Stocktake 2025*. NewClimate Institute, Oxford Net Zero, Energy and Climate Intelligence Unit and Data-Driven EnviroLab.

Newton, Peter, Nicole Civita, Lee Frankel-Goldwater, Katharine Bartel, and Colleen Johns. 2020. "What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes." *Frontiers in Sustainable Food Systems* 4 (October). https://doi.org/10.3389/fsufs.2020.577723.

NFS. 2021. *National Food Strategy: An Independent Review for Government--The Report*.

NFU. 2021. "British Farming: Setting the Standard."

NFU. 2022. "Methane, Ruminant Livestock and Diet." https://www.nfuonline.com/news/methane-ruminant-livestock-and-diet/.

Nordbeck, Ralf, Karl Hogl, and Lena Schaller. 2025. "The Integration of Peatlands into the EU Common Agricultural Policy: Recent Progress and Remaining Challenges." *Environmental Science & Policy* 169 (July): 104077. https://doi.org/10.1016/j.envsci.2025.104077.

Nordhaus, William D. 2017. “Revisiting the Social Cost of Carbon.” *Proceedings of the National Academy of Sciences* 114 (7): 1518–23. https://doi.org/10.1073/pnas.1609244114.

Ocko, Ilissa B., Steven P. Hamburg, Daniel J. Jacob, et al. 2017. “Unmask Temporal Trade-Offs in Climate Policy Debates.” *Science* 356 (6337): 492–93. https://doi.org/10.1126/science.aaj2350.

O’Malley, Jane, Stephanie Searle, and Nikita Pavlenko. 2021. *Indirect Emissions from Waste and Residue Feedstocks: 10 Case Studies from the United States*. White Paper. ICCT.

Palm, Cheryl, Humberto Blanco-Canqui, Fabrice DeClerck, Lydiah Gatere, and Peter Grace. 2014. “Conservation Agriculture and Ecosystem Services: An Overview.” *Agriculture, Ecosystems & Environment*, Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia, vol. 187 (April): 87–105. https://doi.org/10.1016/j.agee.2013.10.010.

Pe’er, Guy, Yves Zinngrebe, Francisco Moreira, et al. 2019. “A Greener Path for the EU Common Agricultural Policy.” *Science* 365 (6452): 449–51.

Perfecto, Ivette, John Vandermeer, Alex Mas, and Lorena Soto Pinto. 2005. “Biodiversity, Yield, and Shade Coffee Certification.” *Ecological Economics* 54 (4): 435–46. https://doi.org/10.1016/j.ecolecon.2004.10.009.

Peters, Glen P. 2008. “From Production-Based to Consumption-Based National Emission Inventories.” *Ecological Economics* 65 (1): 13–23. https://doi.org/10.1016/j.ecolecon.2007.10.014.

Peters, Glen P., and Edgar G. Hertwich. 2008. “Post-Kyoto Greenhouse Gas Inventories: Production versus Consumption.” *Climatic Change* 86 (1): 51–66. https://doi.org/10.1007/s10584-007-9280-1.

Pierrehumbert, R. T. 2014. “Short-Lived Climate Pollution.” *Annual Review of Earth and Planetary Sciences* 42 (1): 341–79. https://doi.org/10.1146/annurev-earth-060313-054843.

Place, S. E., C. J. McCabe, and F. M. Mitloehner. 2022. “Symposium Review: Defining a Pathway to Climate Neutrality for US Dairy Cattle Production.” *Journal of Dairy Science* 105 (10): 8558–68. https://doi.org/10.3168/jds.2021-21413.

Plevin, Richard J., Michael O’Hare, Andrew D. Jones, Margaret S. Torn, and Holly K. Gibbs. 2010. “Greenhouse Gas Emissions from Biofuels’ Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated.” *Environmental Science & Technology* 44 (21): 8015–21. https://doi.org/10.1021/es101946t.

Ponsioen, T. C., and T. J. Blonk. 2012. “Calculating Land Use Change in Carbon Footprints of Agricultural Products as an Impact of Current Land Use.” *Journal of Cleaner Production*, Working towards a more sustainable agri-food industry: Main findings from the Food

LCA 2010 conference in Bari, Italy, vol. 28 (June): 120–26. https://doi.org/10.1016/j.jclepro.2011.10.014.

Poore, J., and T. Nemecek. 2018. "Reducing Food's Environmental Impacts through Producers and Consumers." *Science* 360 (6392). https://ora.ox.ac.uk/objects/uuid:b0b53649-5e93-4415-bf07-6b0b1227172f.

Power, Michael. 2004. "Counting, Control and Calculation: Reflections on Measuring and Management." *Human Relations* 57 (6): 765–83. https://doi.org/10.1177/0018726704044955.

Prasanna, S., Praveen Verma, and Suman Bodh. 2025. "The Role of Food Industries in Sustainability Transition: A Review." *Environment, Development and Sustainability* 27 (7): 15113–33. https://doi.org/10.1007/s10668-024-04642-1.

Ramankutty, Navin, Amato T. Evan, Chad Monfreda, and Jonathan A. Foley. 2008. "Farming the Planet: 1. Geographic Distribution of Global Agricultural Lands in the Year 2000." *Global Biogeochemical Cycles* 22 (1). https://doi.org/10.1029/2007GB002952.

Ranganathan, Janet, Richard Waite, Tim Searchinger, and Jessica Zionts. 2020. *Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change*. May 12. https://www.wri.org/insights/regenerative-agriculture-good-soil-health-limited-potential-mitigate-climate-change.

Reisinger, Andy. 2024. "Why Addressing Methane Emissions Is a Non-Negotiable Part of Effective Climate Policy." *Frontiers in Science* 2 (July). https://doi.org/10.3389/fsci.2024.1451011.

Reisinger, Andy, Harry Clark, Annette L. Cowie, et al. 2021. "How Necessary and Feasible Are Reductions of Methane Emissions from Livestock to Support Stringent Temperature Goals?" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379 (2210): 20200452. https://doi.org/10.1098/rsta.2020.0452.

Resare Sahlin, Kajsa, and Joanna Trewern. 2022. "A Systematic Review of the Definitions and Interpretations in Scientific Literature of 'Less but Better' Meat in High-Income Settings." *Nature Food* 3 (6): 454–60. https://doi.org/10.1038/s43016-022-00536-5.

Rhodes, Christopher J. 2017. "The Imperative for Regenerative Agriculture." *Science Progress* 100 (1): 80–129. https://doi.org/10.3184/003685017X14876775256165.

Ridoutt, Bradley G., and Stephan Pfister. 2010. "A Revised Approach to Water Footprinting to Make Transparent the Impacts of Consumption and Production on Global Freshwater Scarcity." *Global Environmental Change*, Adaptive Capacity to Global Change in Latin America, vol. 20 (1): 113–20. https://doi.org/10.1016/j.gloenvcha.2009.08.003.

Rimmel, Gunnar, Ronita Ram, and Hammed Afolabi. 2025. "ISSB and Global Standardisation of Sustainability Reporting." In *Accounting for Sustainability*, 2nd ed. Routledge.

Ripple, William J., Pete Smith, Helmut Haberl, Stephen A. Montzka, Clive McAlpine, and Douglas H. Boucher. 2014. "Ruminants, Climate Change and Climate Policy." *Nature Climate Change* 4 (1): 2–5. https://doi.org/10.1038/nclimate2081.

Ritchie, Hannah, Pablo Rosado, and Max Roser. 2022. "Environmental Impacts of Food Production." *Our World in Data*, December 2. https://ourworldindata.org/environmental-impacts-of-food.

Ritchie, Hannah, and Max Roser. 2019. "Half of the World's Habitable Land Is Used for Agriculture." *Our World in Data*, November 11. https://ourworldindata.org/global-land-for-agriculture.

Rocha, Alice. 2022. "GWP* — a Better Way of Measuring Methane and How It Impacts Global Temperatures | CLEAR Center." May 18. https://clear.ucdavis.edu/explainers/gwp-star-better-way-measuring-methane-and-how-it-impacts-global-temperatures.

Rockström, Johan, Owen Gaffney, Joeri Rogelj, Malte Meinshausen, Nebojsa Nakicenovic, and Hans Joachim Schellnhuber. 2017. "A Roadmap for Rapid Decarbonization." *Science* 355 (6331): 1269–71. https://doi.org/10.1126/science.aah3443.

Rockström, Johan, Shakuntala Haraksingh Thilsted, Walter C. Willett, et al. 2025. "The EAT–Lancet Commission on Healthy, Sustainable, and Just Food Systems." *The Lancet* 406 (10512): 1625–700. https://doi.org/10.1016/S0140-6736(25)01201-2.

Rodhe, H. 1990. "A Comparison of the Contribution of Various Gases to the Greenhouse Effect." *Science (New York, N.Y.)* 248 (4960): 1217–19. https://doi.org/10.1126/science.248.4960.1217.

Rogelj, Joeri, Oliver Geden, Annette Cowie, and Andy Reisinger. 2021. "Net-Zero Emissions Targets Are Vague: Three Ways to Fix." *Nature* 591 (7850): 365–68. https://doi.org/10.1038/d41586-021-00662-3.

Rogelj, Joeri, Gunnar Luderer, Robert C. Pietzcker, et al. 2015. "Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C." *Nature Climate Change* 5 (6): 519–27. https://doi.org/10.1038/nclimate2572.

Rogelj, Joeri, and Carl-Friedrich Schleussner. 2019. "Unintentional Unfairness When Applying New Greenhouse Gas Emissions Metrics at Country Level." *Environmental Research Letters* 14 (11): 114039. https://doi.org/10.1088/1748-9326/ab4928.

Rogelj, Joeri, and Carl-Friedrich Schleussner. 2021. "Reply to Comment on 'Unintentional Unfairness When Applying New Greenhouse Gas Emissions Metrics at Country Level.'" *Environmental Research Letters* 16 (6): 068002. https://doi.org/10.1088/1748-9326/ac02ec.

Ruiter, Henri de, Jennie I. Macdiarmid, Robin B. Matthews, Thomas Kastner, Lee R. Lynd, and Pete Smith. 2017. "Total Global Agricultural Land Footprint Associated with UK Food

Supply 1986–2011.” *Global Environmental Change* 43 (March): 72–81. https://doi.org/10.1016/j.gloenvcha.2017.01.007.

Santo, Raychel, and Clara Cho. 2025. “Beef Purchasing in Food Service: Considerations for Companies on Balancing Climate and Other Priorities.” *World Resources Institute*, ahead of print, January. https://doi.org/10.46830/wrirpt.23.00169.

Sarofim, Marcus C., and Michael R. Giordano. 2018. “A Quantitative Approach to Evaluating the GWP Timescale through Implicit Discount Rates.” *Earth System Dynamics* 9 (3): 1013–24. https://doi.org/10.5194/esd-9-1013-2018.

SBTi. 2023. “Forest, Land and Agriculture Science-Based Target-Setting Guidance, Version 1.1.” Science Based Targets Initiative.

Schaffer, Michiel, Bill Hare, and Carl Schleussner (Climate Analytics). 2017. “Why Using 20-Year Global Warming Potentials (GWPs) for Emission….” https://climateanalytics.org/publications/why-using-20-year-global-warming-potentials-gwps-for-emission-targets-are-a-very-bad-idea-for-climate-policy.

Scherer, Laura, Brian Tomasik, Oscar Rueda, and Stephan Pfister. 2018. “Framework for Integrating Animal Welfare into Life Cycle Sustainability Assessment.” *The International Journal of Life Cycle Assessment* 23 (7): 1476–90. https://doi.org/10.1007/s11367-017-1420-x.

Schleussner, Carl-Friedrich, Alexander Nauels, Michiel Schaeffer, William Hare, and Joeri Rogelj. 2019. “Inconsistencies When Applying Novel Metrics for Emissions Accounting to the Paris Agreement.” *Environmental Research Letters* 14 (12): 124055. https://doi.org/10.1088/1748-9326/ab56e7.

Schmidinger, Kurt, and Elke Stehfest. 2012. “Including CO2 Implications of Land Occupation in LCAs—Method and Example for Livestock Products.” *The International Journal of Life Cycle Assessment* 17 (8): 962–72. https://doi.org/10.1007/s11367-012-0434-7.

Schneider, Julia M., Florian Zabel, and Wolfram Mauser. 2022. “Global Inventory of Suitable, Cultivable and Available Cropland under Different Scenarios and Policies.” *Scientific Data* 9 (1): 527. https://doi.org/10.1038/s41597-022-01632-8.

Schoenmaker, Dirk, and Willem Schramade. 2024. “Which Discount Rate for Sustainability?” *Journal of Sustainable Finance and Accounting* 3 (September): 100010. https://doi.org/10.1016/j.josfa.2024.100010.

Schreefel, L., R. P. O. Schulte, I. J. M. de Boer, A. Pas Schrijver, and H. H. E. van Zanten. 2020. “Regenerative Agriculture – the Soil Is the Base.” *Global Food Security* 26 (September): 100404. https://doi.org/10.1016/j.gfs.2020.100404.

Schumer, Clea, Sophie Boehm, Joel Jaeger, et al. 2025. “State of Climate Action 2025.” *World Resources Institute*, ahead of print, October. https://doi.org/10.46830/wrirpt.25.00006.

Scottish Government. 2016. “Economic Report on Scottish Agriculture, Table C2 Crops, Grass and Rough Grazings for Each United Kingdom Country, June 2015.” https://www.gov.scot/publications/economic-report-scottish-agriculture-2016/pages/84/.

Searchinger, Timothy, R. Edwards, D. Mulligan, R. Heimlich, and R. Plevin. 2015. “Environmental Economics. Do Biofuel Policies Seek to Cut Emissions by Cutting Food?” *Science (New York, N.Y.)* 347 (6229): 1420–22. https://doi.org/10.1126/science.1261221.

Searchinger, Timothy, Ralph Heimlich, R. A. Houghton, et al. 2008. “Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change.” *Science* 319 (5867): 1238–40. https://doi.org/10.1126/science.1151861.

Searchinger, Timothy, Liqing Peng, Jessica Zionts, and Richard Waite. 2023. “The Global Land Squeeze: Managing the Growing Competition for Land.” *World Resources Institute*, ahead of print, July. https://doi.org/10.46830/wrirpt.20.00042.

Searchinger, Timothy, Richard Waite, Craig Hanson, Janet Ranganathan, and Emily Matthews. 2019. *Creating a Sustainable Food Future*. https://www.wri.org/research/creating-sustainable-food-future.

Searchinger, Timothy, Stefan Wirsenius, Tim Beringer, and Patrice Dumas. 2018. “Assessing the Efficiency of Changes in Land Use for Mitigating Climate Change.” *Nature* 564 (7735): 7735. https://doi.org/10.1038/s41586-018-0757-z.

Searchinger, Timothy, Jessica Zionts, Liqing Peng, Stefan Wirsenius, Tim Beringer, and Patrice Dumas. 2021. *A Pathway to Carbon Neutral Agriculture in Denmark*. July 5. https://www.wri.org/research/pathway-carbon-neutral-agriculture-denmark.

Shindell, Drew, Martin Manning, Joeri Rogelj, et al. 2025. “Open Letter on ‘No Additional Warming’ Goal – Open Letter to New Zealand Prime Minister Warning against the Adoption of a New Biogenic Methane Target Based on the Goal of ‘No Additional Warming.’” https://biogenicmethane.org/.

Shine, K. P, T. K. Berntsen, J. S. Fuglestvedt, R. B. Skeie, and N. Stuber. 2007. “Comparing the Climate Effect of Emissions of Short- and Long-Lived Climate Agents.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 365 (1856): 1903–14. https://doi.org/10.1098/rsta.2007.2050.

Shine, Keith P. 2000. “Radiative Forcing of Climate Change.” *Space Science Reviews* 94 (1): 363–73. https://doi.org/10.1023/A:1026752230256.

Shine, Keith P. 2009. “The Global Warming Potential—the Need for an Interdisciplinary Retrial: An Editorial Comment.” *Climatic Change* 96 (4): 467–72. https://doi.org/10.1007/s10584-009-9647-6.

Shine, Keith P., Jan S. Fuglestvedt, Kinfe Hailemariam, and Nicola Stuber. 2005. “Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of

Greenhouse Gases." *Climatic Change* 68 (3): 281–302. https://doi.org/10.1007/s10584-005-1146-9.

Siebert, Horst. 2002. *Der Kobra-Effekt: wie man Irrwege der Wirtschaftspolitik vermeidet*. [5. Aufl.], Aktualisierte und vollst. überarb. Neuausg. Dt. Verl.-Anst.

Silverman, David. 2022. *Doing Qualitative Research*. Sixth edition. Sage.

Simmonds, Philippa, Damian Maye, and Julie Ingram. 2025. "Ruminant Livestock and Climate Change: Critical Discourse Moments in Mainstream and Farming Sector News Media." *Agriculture and Human Values* 42 (2): 945–64. https://doi.org/10.1007/s10460-024-10651-7.

Smith, Alison C., Paula A. Harrison, Nicholas J. Leach, et al. 2023. "Sustainable Pathways towards Climate and Biodiversity Goals in the UK: The Importance of Managing Land-Use Synergies and Trade-Offs." *Sustainability Science* 18 (1): 521–38. https://doi.org/10.1007/s11625-022-01242-8.

Smith, Greg S., Francisco Ascui, Anthony P. O'Grady, and Elizabeth Pinkard. 2024. "Indicators for Measuring and Reporting Corporate Nature-Related Impacts, Dependencies, and Risks." *Environmental and Sustainability Indicators* 22 (June): 100351. https://doi.org/10.1016/j.indic.2024.100351.

Smith, M. A., M. Cain, and M. R. Allen. 2021. "Further Improvement of Warming-Equivalent Emissions Calculation." *Npj Climate and Atmospheric Science* 4 (1): 1. https://doi.org/10.1038/s41612-021-00169-8.

Smith, Pete, Daniel Martino, Zucong Cai, et al. 2007. "Greenhouse Gas Mitigation in Agriculture." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1492): 789–813. https://doi.org/10.1098/rstb.2007.2184.

Smith, Pete, Dave Reay, and Jo Smith. 2021. "Agricultural Methane Emissions and the Potential Formitigation." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379 (2210): 20200451. https://doi.org/10.1098/rsta.2020.0451.

Smith, Steve, Naomi Vaughan, Sabine Fuss, et al. 2024. *The State of Carbon Dioxide Removal - 2nd Edition*. https://doi.org/10.17605/OSF.IO/F85QJ.

Smith, Steven J., and M. L. Wigley. 2000. "Global Warming Potentials: 1. Climatic Implications of Emissions Reductions." *Climatic Change* 44 (4): 445–57. https://doi.org/10.1023/A:1005584914078.

Soest, Christian von. 2023. "Why Do We Speak to Experts? Reviving the Strength of the Expert Interview Method." *Perspectives on Politics* 21 (1): 277–87. https://doi.org/10.1017/S1537592722001116.

Sofyan, Ahmad, Agung Irawan, Hendra Herdian, et al. 2022. "Effects of Various Macroalgae Species on Methane Production, Rumen Fermentation, and Ruminant Production: A Meta-Analysis from *in Vitro* and *in Vivo* Experiments." *Animal Feed Science and Technology* 294 (December): 115503. https://doi.org/10.1016/j.anifeedsci.2022.115503.

Sohngen, Brent. 2025. "Why the WRI No Harvest Counterfactual Is the Wrong Approach for Carbon Accounting in Forests." *Global Forests: A Blog about Forests and Economics*. https://u.osu.edu/forest/2025/02/28/why-the-wri-no-harvest-counterfactual-is-the-wrong-approach-for-carbon-accounting-in-forests/.

Soimakallio, Sampo, Annette Cowie, Miguel Brandão, et al. 2015. "Attributional Life Cycle Assessment: Is a Land-Use Baseline Necessary?" *The International Journal of Life Cycle Assessment* 20 (10): 1364–75. https://doi.org/10.1007/s11367-015-0947-y.

Springmann, Marco, Michael Clark, Daniel Mason-D'Croz, et al. 2018. "Options for Keeping the Food System within Environmental Limits." *Nature* 562 (7728): 519–25. https://doi.org/10.1038/s41586-018-0594-0.

Statistics Denmark. 2025. "Cropland." https://www.dst.dk/en/Statistik/emner/erhvervsliv/landbrug-gartneri-og-skovbrug/det-dyrkede-areal.

Steinfeld, Henning, Pierre Gerber, T. Wassenaar, V. Castel, Mauricio Rosales, and C. de Haan. 2006. *Livestock's Long Shadow*. https://www.fao.org/4/a0701e/a0701e00.htm.

Stokstad, Erik. 2019. "Nitrogen Crisis Threatens Dutch Environment—and Economy." *Science* 366 (6470): 1180–81. https://doi.org/10.1126/science.366.6470.1180.

Strassburg, Bernardo B. N., Agnieszka E. Latawiec, Luis G. Barioni, et al. 2014. "When Enough Should Be Enough: Improving the Use of Current Agricultural Lands Could Meet Production Demands and Spare Natural Habitats in Brazil." *Global Environmental Change* 28 (September): 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001.

Strong, Jason. 2023. "MLA: Productivity, Profitability and Sustainability – Delving Deeper into the CN30 Goal." *Beef Central*, August 31. https://www.beefcentral.com/carbon/mla-productivity-profitability-and-sustainability-delving-deeper-into-the-cn30-goal/.

Styles, David, Colm Duffy, Rémi Prudhomme, George Bishop, Mary Ryan, and Cathal O'Donoghue. 2024. *Towards a Climate-Neutral Land Sector by 2050: Scenarios Quantifying Land-Use & Emissions Transitions Towards Equilibrium with Removals (SeQUEsTER)*. No. 457. Environmental Protection Agency.

Styles, David, Jalil Yesufu, Martin Bowman, A. Prysor Williams, Colm Duffy, and Karen Luyckx. 2022. "Climate Mitigation Efficacy of Anaerobic Digestion in a Decarbonising Economy." *Journal of Cleaner Production* 338 (March): 130441. https://doi.org/10.1016/j.jclepro.2022.130441.

Tanaka, Katsumasa, and Brian C. O'Neill. 2018. "The Paris Agreement Zero-Emissions Goal Is Not Always Consistent with the 1.5 °C and 2 °C Temperature Targets." *Nature Climate Change* 8 (4): 4. https://doi.org/10.1038/s41558-018-0097-x.

Taylor, John R. 2022. *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. Third edition. University Science Books.

Taylor, Rod, and Charlotte Streck. 2018. "The Elusive Impact of the Deforestation-Free Supply Chain Movement, Working Paper." World Resources Instutute.

Teagasc. 2017. "Agriculture in Ireland." *Teagasc | Agriculture and Food Development Authority*. https://teagasc.ie/rural-economy/rural-economy/agri-food-business/agriculture-in-ireland/.

Theurl, Michaela C., Christian Lauk, Gerald Kalt, et al. 2020. "Food Systems in a Zero-Deforestation World: Dietary Change Is More Important than Intensification for Climate Targets in 2050." *Science of The Total Environment* 735 (September): 139353. https://doi.org/10.1016/j.scitotenv.2020.139353.

Thomas, Chris D., Barbara J. Anderson, Atte Moilanen, et al. 2013. "Reconciling Biodiversity and Carbon Conservation." *Ecology Letters* 16 (s1): 39–47. https://doi.org/10.1111/ele.12054.

Thompson, L. R., C. M. Salisbury, and M. R. Beck. 2026. "Climate Goals in Ruminant Agriculture: The Complicated Science of Goal Setting." *Frontiers in Sustainable Food Systems* 10 (February). https://doi.org/10.3389/fsufs.2026.1718477.

Tilman, David, Christian Balzer, Jason Hill, and Belinda L. Befort. 2011. "Global Food Demand and the Sustainable Intensification of Agriculture." *Proceedings of the National Academy of Sciences* 108 (50): 20260–64. https://doi.org/10.1073/pnas.1116437108.

Tseten, Tenzin, Rey Anthony Sanjorjo, Moonhyuk Kwon, and Seon-Won Kim. 2022. "Strategies to Mitigate Enteric Methane Emissions from Ruminant Animals." *Journal of Microbiology and Biotechnology* 32 (3): 269–77. https://doi.org/10.4014/jmb.2202.02019.

Tuomisto, H. L., I. D. Hodge, P. Riordan, and D. W. Macdonald. 2012. "Comparing Energy Balances, Greenhouse Gas Balances and Biodiversity Impacts of Contrasting Farming Systems with Alternative Land Uses." *Agricultural Systems* 108 (April): 42–49. https://doi.org/10.1016/j.agsy.2012.01.004.

UK Soy Manifesto. 2020. "The Manifesto | The UK Soy Manifesto." https://dev.com:8888/.

UNEP, U. N. 2021. *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions | UNEP - UN Environment Programme*. United Nations Environment Programme. https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

UNFCCC. 1997. "Kyoto Protocol to the United Nations Framework Convention on Climate Change."

UNFCCC. 2015. "Paris Agreement to the United Nations Framework Convention on Climate Change."

United Kingdom. 2020. "United Kingdom, 2020. Convention. Common Reporting Format (CRF) Table." https://unfccc.int/documents/627795.

United Nations. 1992. "United Nations Framework Conventions on Climate Change." UN.

Villoria, Nelson, Rachael Garrett, Florian Gollnow, and Kimberly Carlson. 2022. "Leakage Does Not Fully Offset Soy Supply-Chain Efforts to Reduce Deforestation in Brazil." *Nature Communications* 13 (1): 5476. https://doi.org/10.1038/s41467-022-33213-z.

Vries, M. de, C. E. van Middelaar, and I. J. M. de Boer. 2015. "Comparing Environmental Impacts of Beef Production Systems: A Review of Life Cycle Assessments." *Livestock Science* 178 (August): 279–88. https://doi.org/10.1016/j.livsci.2015.06.020.

Vuuren, Detlef P. van, Keywan Riahi, Richard Moss, et al. 2012. "A Proposal for a New Scenario Framework to Support Research and Assessment in Different Climate Research Communities." *Global Environmental Change* 22 (1): 21–35. https://doi.org/10.1016/j.gloenvcha.2011.08.002.

Waite, Richard, Jessica Zionts, and Clara Cho. 2024. "Toward 'Better' Meat? Aligning Meat Sourcing Strategies with Corporate Climate and Sustainability Goals." *World Resources Institute*, ahead of print, April. https://doi.org/10.46830/wrirpt.22.00006.

Watson, Robert, Ian Noble, Bert Bolin, N. H. Ravindranath, David Verardo, and David Dokken. 2000. *IPCC Special Report on Land Use, Land-Use Change and Forestry*. IPCC.

WBCSD, and WRI, eds. 2004. *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*. Rev. ed. World Business Council for Sustainable Development ; World Resources Institute.

WCC. 2024. "Woodland Carbon Code Carbon Calculation Spreadsheet Version 2.4.1." https://woodlandcarboncode.org.uk/standard-and-guidance/3-carbon-sequestration/3-3-project-carbon-sequestration.

Weaver, Kathryn. 2018. "Pragmatic Paradigm." In *The SAGE Encyclopedia of Educational Research, Measurement, and Evaluation*. SAGE Publications, Inc. https://doi.org/10.4135/9781506326139.

Wengraf, Tom. 2011. *Qualitative Research Interviewing: Biographic Narrative and Semi-Structured Methods*. Repr. Sage.

Westaway, Sally, Ian Grange, Jo Smith, and Laurence G. Smith. 2023. "Meeting Tree Planting Targets on the UK's Path to Net-Zero: A Review of Lessons Learnt from 100 Years of

Land Use Policies." *Land Use Policy* 125 (February): 106502. https://doi.org/10.1016/j.landusepol.2022.106502.

Wheatley, Joe. 2024. *Ireland's Warming Impact*. University College Dublin.

Wicke, Birka, Pita Verweij, Hans van Meijl, Detlef P. van Vuuren, and Andre PC Faaij. 2012. "Indirect Land Use Change: Review of Existing Models and Strategies for Mitigation." *Biofuels* 3 (1): 87–100. https://doi.org/10.4155/bfs.11.154.

Wirsenius, Stefan, Oliver James, Tim Beringer, and Timothy Searchinger. 2025. "The Full Climate Costs of Agriculture Including Foregone Land Carbon Storage." Preprint, Research Square, June 5. https://doi.org/10.21203/rs.3.rs-6678069/v1.

Wirsenius, Stefan, Oliver James, Tim Beringer, and Timothy D. Searchinger. In Review. *The Full Climate Costs of Agriculture Including Foregone Land Carbon Storage*.

Wirsenius, Stefan, Tim Searchinger, Jessica Zionts, Liqing Peng, Tim Beringer, and Patrice Dumas. 2020. *Comparing the Life Cycle Greenhouse Gas Emissions of Dairy and Pork Systems Across Countries Using Land-Use Carbon Opportunity Costs*. May 29. https://www.wri.org/research/comparing-life-cycle-greenhouse-gas-emissions-dairy-and-pork-systems-across-countries.

Wisser, Dominik, Danielle S. Grogan, Lydia Lanzoni, et al. 2024. "Water Use in Livestock Agri-Food Systems and Its Contribution to Local Water Scarcity: A Spatially Distributed Global Analysis." *Water* 16 (12): 12. https://doi.org/10.3390/w16121681.

WMO. 1991. *Scientific Assessment of Ozone Depletion*.

Wollenberg, Eva, Meryl Richards, Pete Smith, et al. 2016. "Reducing Emissions from Agriculture to Meet the 2 °C Target." *Global Change Biology* 22 (12): 3859–64. https://doi.org/10.1111/gcb.13340.

WRAP, and IGD. 2024. *A Net Zero Transition Plan for the UK Food System*.

WRI and WBCSD. 2022a. *Land Sector and Removals Guidance: Part 1: Accounting and Reporting Requirements and Guidance, Supplement to the GHG Protocol Corporate Standard and Scope 3 Standard (Draft for Pilot Testing and Review)*.

WRI and WBCSD. 2022b. "List of Land Sector Calculation Resources- Greenhouse Gas Protocol: Land Sector and Removals Guidance." Version 1.2. https://ghgprotocol.org/land-sector-and-removals-guidance.

WRI and WBCSD. 2026. *Land Sector and Removals Standard, Version 1.0: Agriculture and CO2 Removal Technologies*. World Resources Institute and World Business Council for Sustainable Development.

WRI and WBCSD. 2011. *Corporate Value Chain (Scope 3) Accounting and Reporting Standard*.

Wunder, Sven, Cecilia Fraccaroli, Joseph W. Bull, et al. 2025. "Biodiversity Credits: An Overview of the Current State, Future Opportunities, and Potential Pitfalls." *Business Strategy and the Environment* 34 (7): 8470–99. https://doi.org/10.1002/bse.70018.

WWF. 2017. *Appetite for Destruction*. WWF International.

WWF. 2022. *The Future of Feed: How Low Opportunity Cost Livestock Feed Could Support a More Regenerative UK Food System*. World Wildlife Fund.

Xie, Xin, Yurong Cao, Qiushuang Li, et al. 2025. "Mitigating Enteric Methane Emissions: An Overview of Methanogenesis, Inhibitors and Future Prospects." *Animal Nutrition* 21 (June): 84–96. https://doi.org/10.1016/j.aninu.2025.02.001.

Xu, Xiaoming, Prateek Sharma, Shijie Shu, et al. 2021. "Global Greenhouse Gas Emissions from Animal-Based Foods Are Twice Those of Plant-Based Foods." *Nature Food* 2 (9): 724–32. https://doi.org/10.1038/s43016-021-00358-x.

Yarlagadda, Brinda, Xin Zhao, Gokul Iyer, Thomas Wild, Nathan Hultman, and Jonathan Lamontagne. 2025. "Emissions Leakage and Economic Losses May Undermine Deforestation-Linked Oil Crop Import Restrictions." *Nature Communications* 16 (1): 1520. https://doi.org/10.1038/s41467-025-56693-1.

Zerbe, Maximilian, Daniel Mörlein, and Stefan Josef Hörtenhuber. 2025. "Towards Climate Neutrality: Comparison of Mitigation Strategies for Agricultural Emissions Using GWP100 and GWP* Metrics." *Environmental Challenges* 18 (April): 101060. https://doi.org/10.1016/j.envc.2024.101060.

Zionts, Jessica. 2018. "Policy Implications of Metric Selection on NDCs and the Global Stocktake [Unpublished Dissertation]." University of Oxford.

Zionts, Jessica, Harriet Bartlett, Tim Searchinger, and Myles Allen. 2025. "The Utility of Novel Environmental Impact Metrics in UK Ruminant Mitigation." *Environmental Research: Food Systems* 2 (2): 025009. https://doi.org/10.1088/2976-601x/add93e.

ZuivelNL. 2024. *Dutch Dairy in Figures: 2024*. ZuivelNL.

Zurek, Monika, Aniek Hebinck, and Odirilwe Selomane. 2022. "Climate Change and the Urgency to Transform Food Systems." *Science* 376 (6600): 1416–21. https://doi.org/10.1126/science.abo2364.

Appendix I

This Appendix contains the Supplementary Materials of Chapter 4 (Paper 1).

I.1 Formulas

Global Warming Potential (GWP) is calculated as:

$$GWP_i(H) = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_C(t)dt}$$

Where 'i' is a given greenhouse gas, H is the chosen time horizon (20, 100, 500, etc. years), and RF is the radiative forcing. The numerator is the integrated radiative forcing of GHG 'i' due to a pulse emission in year 0, and the denominator is the integrated radiative forcing of carbon dioxide. Based on the IPCC First Assessment Report

GWP* is calculated as:

$$GWP^* = \left(128\ x\ E_{CH4}(t)\right) - (120\ x\ E_{CH4}(t-20))$$

Where E_{CH4} is a quantity of methane emissions emitted in year 't' (M. A. Smith et al. 2021).

GWP*c, which is an annualization of the cumulative emissions of GWP*, is calculated as:

$$GWP^*c = \frac{\int_y^t GWP^*(x)dx}{t-y}$$

Where *y* is the starting year and *t* is the ending year of the annualized period. In the case of this analysis, *y* is 2050 and *t* is 2100. Thus, we can account for the fact that the benefits of decreased (or consequences of increased) methane emissions pre-2050 are temporary to holistically account for end-of-century effects.

The Carbon Opportunity Cost of a given land-based product can be calculated either as a ‘carbon loss’ looking into the past at historical carbon loss or a ‘carbon gain,’ estimating foregone sequestration into the future.

$$COC = \frac{Potential\ Carbon\ Stock - Actual\ Carbon\ Stock}{Total\ Product\ Output}$$

Where the numerator and denominator are both time-discounted, and calculated globally for each land-based product (Searchinger et al. 2018).

I.2 Sensitivity for Feed Baskets

Cattle in the UK consume some combination of domestic and imported feeds, as well as grazed forages. However, the exact quantities of feeds consumed by cattle are difficult to discern both at a national and farm level.

The land costs associated with imported soy (using dLUC) are one of the main points of contention explored in this analysis, as well as a source of uncertainty. Our estimate of 37% of imported and domestically produced feed going to cattle is crude, based on publicly available data. Thus, we explore potential alternative scenarios based on other estimates of soy use or potential policy interventions to understand how shifts in the feed basket due to these uncertainties might impact the land cost calculations using both COC and dLUC relative to the 2019 baseline calculated in the analysis.

The first alternative scenario is based on a consultant report on UK soy consumption, which estimates that 16% of imported soy is used for cattle (KPMG and IDH 2017). In this scenario, the imported COC decreases slightly, whereas imported dLUC decreases by more than half due to the high dLUC factor of imported soy as shown in Table I.1.

Many large UK companies from throughout the food system have committed to eliminating deforestation-linked soy from their supply chains (UK Soy Manifesto 2020). In practice, this means that companies shift suppliers to farms in countries that have not recently cleared land, or shift within a country that has cleared land to farms that have not been recently cleared. As shown in Scenario 2 in Table I.1, this does not change COC whatsoever because this metric is calculated globally, and does not change based on which country or farm the soy comes from. However, land costs using dLUC are dominated by imported soy from South America where deforestation is occurring. Thus, eliminating consumption of soy from regions where deforestation is occurring results in a dLUC factor of 0 for imported soy. This reduces imported dLUC by 92%. This demonstrates that changing the sourcing region of soy represents a significant mitigation opportunity using dLUC, but not using COC.

The third and fourth scenarios are based on calls from environmental and agricultural interest groups to replace imported soy with domestically grown pulses and legumes (Landworkers' Alliance et al. 2023). The report that analyzes this intervention is primarily relevant to poultry and pork production, which consume most of the UK's imported soy. However, we include this scenario because cattle do use some soy, and as shown in the previous two scenarios, it strongly influences land costs even when it makes up a small fraction of the feed basket. We therefore include scenarios that replace 50% of imported soy with domestic beans and peas.

Soybeans contain around 37% protein by weight, while beans and peas each contain 21%. As a result, more beans and peas are required to replace an equal amount of protein from soy. In both scenarios, replacing 50% of imported soy reduces dLUC by about half, while imported COCs decrease by less than 20%. However, beans and pulses have higher COCs than soybeans because they must be grown on lengthy rotations with many other crops, thus have larger land footprints. Even though some of the global soy supply is grown in the tropics, much of it is grown in North America, and tropical yields are very high. Thus, domestic COC increases by 24% for peas and 65% for beans.

These results illustrate that interventions that reduce dLUC do not necessarily reduce COC, meaning that the choice of metric matters in the development of strategies to reduce land use costs.

Table I.1: Land use costs using COC and dLUC for four feed basket scenarios where the quantity and source of imported soy vary.

Scenario	Domestic COC	Imported COC	COC total (Mt CO_2e)	Imported dLUC
2019 Baseline (37% of imported soy is used for cattle)	73.04	5.55	78.59	7.81
KPMG & IDH (16% of imported soy is used for cattle)	73.04	4.39	77.44	3.71
Zero Deforestation	73.04	5.55	78.59	0.59
Beans replace 50% imported soy	94.33	4.53	98.86	4.20
Peas replace 50% imported soy	81.06	4.53	85.60	4.20

I.3 Data and emissions factors

Note that the percent reductions do not reflect policy-based projections, but rather represent various levels of hypothetical mitigation ambition.

Table I.2: Percentage reductions of each emissions or land cost category for four 2050 scenarios based on varying levels of mitigation ambition. The scenarios are described in Table 1 in the main text. Note that the percentage reductions for the AET and BRT scenarios are applied after the INT scenario. For example, in the BRT scenario, enteric methane is reduced by 55% relative to the emissions level after the 34% reduction from INT. If the baseline for enteric methane were 100 kt of methane, emissions in 2050 under the BRT scenario would be 100 x 34% x 55% = 18.7 kt.

Emissions Category	**BAU**	**INT**	**AET (in addition to INT)**	**BRT (in addition to INT)**
Enteric methane	0%	34%	0%	55%
Manure management CH4	0%	41%	40%	85%
Manure management N2O	0%	32%	40%	85%
Applied N (manure)	0%	29%	50%	50%
Applied N (synthetic)	0%	16%	64%	70%
Applied N (crop residues)	0%	21%	50%	50%
Indirect N	0%	21%	50%	50%
On-farm energy	0%	17%	90%	90%
Field input production	0%	16%	90%	90%
Peatlands	0%	0%	0%	95%
Lime and urea	0%	0%	0%	0%
Imported PEMs	0%	13%	0%	0%
Imported COCs	0%	13%	0%	25%
Imported dLUC	0%	12%	0%	25%
Domestic COCs	0%	45%	0%	25%

Table I.3: Feed Conversion Efficiency (FCE) improvements by crop type. These figures represent how much less of each crop is required due to improvements in digestibility. They come from prior analysis of the Danish land sector (Searchinger et al. 2021).

FCE improvements	% improvement
Energy concentrates	9%
Protein concentrates	11%
Grass-legume silage	49%
maize silage	51%

Table I.4: Projected ambitious crop yield gains for Northwestern Europe from previous analysis of the Danish land sector (Searchinger et al. 2021).

Ambitious gains	% increase
Barley	31.5%
Wheat	18%
Rapeseed	43.5%
Maize	51%
Rye & triticale	45%
Rest	22.5%

Table I.5: Percent reductions of emissions by category due to improvements in FCE based on previous analysis of the Danish land sector (Searchinger et al. 2021).

Emissions category	% Emissions reductions
Enteric	34%
Manure Management (CH_4)	41%
Manure Management (N_2O)	32%
Field operations	35%
Barn operations	22%

Table I.6: Applied nitrogen rates from the UK NIR Annex Table A.3.3.9

Crop	Additional nitrogen (kg N/ha)
Wheat	182.1
Barley	121.9
Oats	101.5
Rapeseed	173.5
Sugar beet	210.0
Peas	0
Field beans	0.73
Pasture	50.0

Table I.7: Historical emissions (in megatonnes) from 1990 to 2019 from various sources described in the Methods. Historical emissions are required primarily for the calculation of GWP and contribution to warming.*

	ch4	**ch4**	**n2o**	**n2o**	**co2**	**co2**
	Enteric methane	Manure management	Manure management	Applied nitrogen	On-farm energy	Field input production
1990	0.76	0.12	0.01	0.01	0.32	0.74
1991	0.74	0.12	0.01	0.01	0.32	0.74
1992	0.74	0.12	0.01	0.01	0.32	0.75
1993	0.74	0.12	0.01	0.01	0.32	0.75
1994	0.75	0.12	0.01	0.01	0.32	0.75
1995	0.75	0.12	0.01	0.01	0.32	0.75
1996	0.77	0.12	0.01	0.01	0.32	0.75
1997	0.75	0.12	0.01	0.01	0.32	0.76
1998	0.74	0.12	0.01	0.01	0.32	0.76
1999	0.74	0.12	0.01	0.01	0.32	0.76
2000	0.72	0.12	0.01	0.01	0.32	0.76
2001	0.70	0.12	0.01	0.01	0.32	0.76
2002	0.69	0.12	0.01	0.01	0.31	0.77
2003	0.70	0.12	0.01	0.01	0.31	0.77
2004	0.70	0.12	0.01	0.01	0.31	0.77
2005	0.71	0.12	0.01	0.01	0.31	0.77
2006	0.70	0.12	0.01	0.01	0.31	0.77
2007	0.69	0.12	0.01	0.01	0.31	0.78
2008	0.67	0.12	0.01	0.01	0.31	0.78
2009	0.67	0.12	0.01	0.01	0.31	0.78
2010	0.67	0.12	0.01	0.01	0.31	0.78
2011	0.66	0.12	0.01	0.01	0.31	0.78
2012	0.66	0.12	0.01	0.01	0.31	0.79
2013	0.65	0.12	0.01	0.01	0.31	0.79
2014	0.67	0.12	0.01	0.01	0.30	0.79
2015	0.67	0.12	0.01	0.01	0.30	0.79
2016	0.67	0.12	0.01	0.01	0.30	0.79
2017	0.67	0.12	0.01	0.01	0.30	0.80
2018	0.66	0.12	0.01	0.01	0.30	0.80
2019	0.66	0.12	0.01	0.01	0.30	0.80

	co2	ch4	n2o	co2	co2	co2	co2	co2
	Peatlands	Peatlands	Peatlands	Lime and urea application	Imported PEMs	Imported COC	Imported dLUC	Domestic COC
1990	4.19	0.02	0.00	0.86	0.77	4.43	6.17	72.05
1991	4.18	0.02	0.00	0.86	0.78	4.47	6.22	72.09
1992	4.17	0.02	0.00	0.86	0.79	4.51	6.28	72.12
1993	4.16	0.02	0.00	0.86	0.80	4.55	6.34	72.15
1994	4.15	0.02	0.00	0.86	0.82	4.59	6.39	72.19
1995	4.13	0.02	0.00	0.86	0.83	4.63	6.45	72.22
1996	4.12	0.02	0.00	0.86	0.84	4.66	6.51	72.26
1997	4.11	0.02	0.00	0.85	0.85	4.70	6.56	72.29
1998	4.10	0.02	0.00	0.85	0.87	4.74	6.62	72.32
1999	4.08	0.02	0.00	0.85	0.88	4.78	6.68	72.36
2000	4.07	0.02	0.00	0.85	0.89	4.82	6.73	72.39
2001	4.06	0.02	0.00	0.85	0.90	4.86	6.79	72.43
2002	4.05	0.02	0.00	0.85	0.92	4.90	6.85	72.46
2003	4.04	0.02	0.00	0.85	0.93	4.93	6.90	72.50
2004	4.02	0.02	0.00	0.85	0.94	4.97	6.96	72.53
2005	4.01	0.02	0.00	0.85	0.95	5.01	7.02	72.56
2006	4.00	0.02	0.00	0.85	0.96	5.05	7.07	72.60
2007	3.99	0.02	0.00	0.85	0.98	5.09	7.13	72.63
2008	3.97	0.02	0.00	0.85	0.99	5.13	7.19	72.67
2009	3.96	0.02	0.00	0.85	1.00	5.17	7.24	72.70
2010	3.95	0.02	0.00	0.85	1.01	5.20	7.30	72.73
2011	3.94	0.02	0.00	0.85	1.03	5.24	7.36	72.77
2012	3.92	0.02	0.00	0.85	1.04	5.28	7.42	72.80
2013	3.91	0.02	0.00	0.85	1.05	5.32	7.47	72.84
2014	3.90	0.02	0.00	0.85	1.06	5.36	7.53	72.87
2015	3.89	0.02	0.00	0.85	1.08	5.40	7.59	72.90
2016	3.88	0.02	0.00	0.85	1.09	5.44	7.64	72.94
2017	3.86	0.02	0.00	0.85	1.10	5.47	7.70	72.97
2018	3.85	0.02	0.00	0.85	1.11	5.51	7.76	73.01
2019	3.84	0.02	0.00	0.85	1.13	5.55	7.81	73.04

Table I.8: Quantities of domestically produced feeds used for cattle and COC emissions factors at both the Regional (Europe) and Global levels.

Total Domestic feed used for cattle	kilotonnes per year	Regional COC (kg CO_2e per kg fresh)	Global COC (kg CO_2e per kg fresh)
Wheat	2,691.43	2.1	1.79
Barley	1,500.37	2.32	2.36
Oats	118.63	2.21	2.075
Rapeseed	497.25	4.03	5.21
Sugar beet	1,141.80	0.18	0.17
Peas	40.38	4.03	5.21
Field beans	182.24	14.9	9.85
Grass	81,330.31	0.73	0.73

Table I.9: Quantities of imported feed used for cattle with the parameters required to calculate land costs under both dLUC and COC as well as PEMs.

					t/ha	t/ha	t/ha
Total imported feed used for cattle	kilotonnes per year	Regional COC (kg CO_2e per kg fresh)*	Global COC (kg CO_2e per kg fresh)	PEM (kg CO_2e/kg)	dLUC CO_2	dLUC CH_4	dLUC N_2O
Wheat	424.81	2.1	1.79	0.59	0.16	1.17E-06	1.18E-08
Barley	21.94	2.32	2.36	0.48	0.00	1.67E-06	1.69E-08
Oats	3.77	2.21	2.075	0.67	0.00	1.91E-07	2.61E-09
Rapeseed	119.25	4	5.21	0.85	1.18	2.67E-07	3.64E-09
Sugar beets	1,312.15	0.18	0.17	0.26	0.00	3.80E-07	5.19E-09
Peas	4.05	4.03	5.21	0.50	12.44	4.60E-07	6.28E-09
Beans	17.82	14.9	9.85	0.60	21.01	5.76E-07	7.87E-09
Maize products	183.71	1.68	2.3	0.43	5.68	7.52E-07	1.03E-08
Soya cake and meal	424.40	4.4	5.21	0.31	66.81	9.68E-07	1.32E-08
Sunflower cake and meal	141.33	4.6	3.51	0.72	0.00	1.25E-06	1.70E-08
Other oilseeds	185.32	3.56	3.67	0.51	0.00	1.61E-06	2.21E-08

Table I.10: De-annualized COC values for all feed crops to be used in cumulative accounting of COCs from the Supplementary Materials of Searchinger et al. (2018).

Crop	tCO_2e/t fresh weight
Wheat	59.8
Barley	79.4
Oats	79.4
Rapeseed	176.2
Sugar beets	5.9
Peas	227.6
Beans	419.9
Maize products	74.9
Soya cake and meal	166.4
Sunflower cake and meal	154.0
Other oilseeds	138.7
Grass	45.9

I.4 Definitions of Emissions Categories

Table I.11: Descriptions of the emissions categories used in the analysis, the level of possible GHG disaggregation, and indication of whether the category is used in the IPCC AFOLU reporting guidance. Based on Table ES-1 of Searchinger et al. (2021).

Emissions Categories	**Greenhouse Gas(es)**	**Description**	**Included in IPCC AFOLU guidance?**
Enteric Fermentation	CH_4	Anaerobic digestion of plant matter not consumable by humans in ruminant livestock (cows, sheep)	Yes
Manure Management	CH_4, N_2O	Emissions from solid and liquid waste: anaerobic volatilization of methane, and aerobic nitrification of nitrous oxide	Yes
Application of Manure, Synthetic Fertilizer, and Crop Residue	N_2O	Direct nitrification emissions from applied sources of nitrogen	Yes
Field Input Production	CO_2e	Emissions upstream from the farm associated with the manufacture of synthetic fertilizers and pesticides typically reported as an aggregated emissions factor	No
Indirect Emissions from Soil Management	N_2O	Nitrification that results from atmospheric deposition and leaching, which may occur outside of the farm	Yes
Production of Imported Feed	CO_2e	Emissions associated with the production of feed off-site, reported as a global aggregate emissions factor	No
Liming and Urea Application	CO_2	Limestone and urea are used to adjust acidity on managed soils	Yes
On-Farm Energy	CO_2e	Emissions resulting from energy consumption on the farm, such as for farm equipment or barn operations	No
Direct Land Use Change	CO_2e	Emissions (or removals) that occur when land is converted from one land use category to another	Yes
Carbon Opportunity Cost	CO_2e	Historical carbon loss (or foregone sequestration) due to land being used for producing food, feed, or fiber instead of storing carbon as a natural ecosystem	No

I.5 Sensitivity of Production Increase

Global demand for food, including livestock products, is likely to increase in the coming decades, even with progress on shifting diets and improvements in food loss and waste. The percent increase by 2050 relative to a 2019 baseline, however, is a source of uncertainty in this analysis. Thus, we explored the implications of different future production increases for both the BAU and BRT scenarios.

The sensitivity analysis showed that the impact of a higher percent increase in production in the BAU scenario is greater when using GWP* relative to GWP_{100} because the impact of increased methane under that scenario overshadowed all other emissions increases. In the BAU scenario, lower percent increases result in lower emissions under GWP* compared to GWP_{100}. Conversely, the impact of a higher percent increase in production in the BRT scenario is greater when using GWP_{100} because the benefits of methane reduction in this scenario under GWP* from ambitious mitigation offsets the increases of other emissions sources resulting from increased production. However, in the BRT scenario, emissions under GWP* are always less than emissions under GWP_{100} regardless of the percent increase.

This sensitivity exercise shows that, in a BAU scenario, GWP_{100} appears slightly more favorable only when the production increase is higher, whereas in a more ambitious mitigation scenario, GWP* appears more favorable regardless of the production increase. Thus, the projected production increase is a more sensitive parameter in scenarios of low-to-no mitigation ambition.

Figure I.1: Sensitivity analysis of total production emissions and land use costs under various metric combinations for UK cattle in business-as-usual (BAU, top) and Breakthrough Technologies (BRT, bottom) scenarios for potential projected future increases in beef and dairy production

Appendix II

This Appendix contains Supplementary Materials for Paper 2 (Chapter 5)

Supplement A

I.1 Modules

II.1.1 Crop System

The crop module calculates an on-farm emissions baseline simply by selecting a crop from the dropdown list. The main emissions sources are from applied nitrogen and farm machinery. This data is pulled from national average values, however a user could override this if farm-specific data is available.

II.1.2 Afforestation Calculation

The calculation of the net effect of afforestation begins with inputs about the productivity of the herd of cattle that would be replaced by forest. In this example, we model a beef finishing operation. Users could use the methodology to model a dairy system as well. The default data in this Appendix come from LCA Jebari et al (2025) (Jebari et al. 2025).

Table II.1: User inputs for the afforestation calculation

Livestock Gains	
Number of animals purchased*	30
Starting weight (kg, carcass weight)*	166
Finished weight (kg, carcass weight)*	294
Number of animals sold*	30
Total gains (kg)	3,834
Total gains sold (kg)	3,834
COC per kg gained (kg CO2 per kg gained)[1]	50
COC of gains (kg)	191,700
Feed and Forage	
Feed A*	Wheat
Feed A Quantity (tonnes)*	38.73
Feed A COC per tonne	2.51
Total Feed A COC (tonnes)	97.2123
Feed B*	Rapeseed
Feed B Quantity (tonnes) *	1.92
Feed B COC per tonne	4.62
Total Feed B COC (tonnes)	8.8704
Grazed Area (hectares)*	21

** denotes user input*
[1] Regional COC value for Europe from (Wirsenius et al. In Review)

Table II.2: Annual carbon sequestration rates from the Woodland Carbon Code database used in the baseline, high carbon, and low carbon scenarios for Table 1 in the main text. The baseline tree species and yield class were selected based on the ESC4 online tool's suggestion of compatible tree species for the farm site in the LCA Jebari et al (2025).

Years	High C (CO_2/ha)	Low C (CO_2/ha)	Baseline (CO_2/ha)
0 to 5	2.25	0.06	0.95
6 to 10	6.87	0.19	2.89
11 to 15	20.69	0.58	8.81
16 to 20	28.82	1.78	24.04
21 to 25	14.98	5.42	6.84
26 to 30	14.53	16.55	2.75
Total CO2/ha	440.7	122.9	231.4
Species	Lodgepole Pine	Beech	Corsican Pine
Yield Class	14	4	12
Management	NO_thin	Thinned	Thinned

To run the calculations for the afforestation simulation, users must input farm-specific parameters regarding the herd size, grazed area, and feed use as shown in Table II.1. The farm used in this example uses supplemental wheat and rapeseed feedstuffs. The tool is currently programmed to handle up to two supplementary feeds, which users choose from a dropdown list.

We then estimate 30 years of carbon sequestration due to afforestation. Using the ESC4 tool online, users must select where the farm is located. ESC4 will then provide insights on the most optimal tree species to plant, and the yield class. Users must then input the species, yield class, and whether the forest is thinned in the dropdowns as shown in Table A.3, which then pulls the carbon sequestration rates from the Woodland Carbon Code database. The example shown is based on the location of the farm used for the demonstrative calculation in the main text of this article.

Table II.3: Sample user inputs for tree species, yield class selection, and thinning.

INPUTS	
Tree species planted	Corsican Pine (determined with ESC4)
Yield Class	12
Management	Thinned

II.1.3 Crop Interventions

This calculation runs by selecting an intervention from the dropdown list for the crop selected in the 'Crop System' module. This will generate a figure for the range of net impacts associated with that crop and intervention.

Users must also input the assumed percent reduction in production emissions following an intervention. This can either be a known value using real farm data, from a published LCA, or a reasonable estimate.

II.2 Default data

Table II.4: Default data on the production of domestic feed crops.

Domestic Feed	COC Factor (kg CO2e per kg DM)[1]	UK Yield (tonnes per ha)[2]	Applied Synthetic N (kg/ha)[3]	Applied Organic N (kg/ha)[3]
Wheat	2.51	8	121	77
Barley	2.34	6	81	51
Oats	2.1425	5	67	43
Rapeseed	4.62	3	115	73
Sugar Beet	0.175	68	139	88
Peas	4.62	3	-	-
Beans	12.375	3	0.49	0
Grass	0.73	22	65	41

[1] Searchinger et al (2018) (Searchinger et al. 2018)
[2] DEFRA (DEFRA 2021)
[3] National Inventory Report 2021 Annex Table A.3.3.9 (Brown et al. 2021)

II.3 Literature review on yield

Table II.5: Sources in the literature containing data about the effect of crop farming practices on yield used in this study, including the publications providing raw data, and the meta-analyses used to find the raw data, when relevant.

Meta Study	Source(s)	Intervention	Crop
Cui 2022	Cannell et al 1986 Christian and Bacon 1990	No Till	Wheat
Su 2021	Ball et al 1985 Campbell et al 1986 Newton et al 2012	No Till	Wheat
Su 2021	Giannitsopoulos 2019	No Till	Barley
Pittelkow 2014	Ball et al 1985 Campbell et al 1986 Christian and Bacon 1990 Newton et al 2012 Sharma 1985 Soane and Ball 1998	No Till	Barley
Pittelkow 2014	Soane and Ball 1998 Christian and Bacon 1990	No Till	Rapeseed
Pittelkow 2014	Cannell et al 1986 Christian and Bacon 1990	No Till	Oat
	Abdalla 2019	Cover Crops	Oat
Badgley 2007	Trewavas 2004	Organic	Oat
Badgley 2007	Trewavas 2004 Jenkinson 1994	Organic	Wheat
Badgley 2007	Trewavas 2004	Organic	Beans
Badgley 2007	Trewavas 2004	Organic	Peas
Thapa 2018	Catt 1998	Cover Crops	Cereals
Poore 2018	Lillywhite et al 2007 Williams et al 2006, 2010 Wiltshire et al 2009	Organic	Wheat
Poore 2018	Williams et al 2006	Organic	Maize
Poore 2018	Williams et al 2006	Organic	Barley
Poore 2018	Lillywhite et al 2007 Tzilivakis et al 2005	Organic	Sugar beet
Poore 2018	Williams et al 2006 Wiltshire et al 2009	Organic	Field beans

Poore 2018	Williams et al 2006, 2010	Organic	Rapeseed
Conservation Evidence	McGrath 1990	Manage Insecticides	Barley
Conservation Evidence	Rahn 2009	Crop Residues	Barley
Conservation Evidence	Quinton 2004	No Till	Grains
Conservation Evidence	Linzel 1986	Reduced Fertilizers	Wheat
Smith 2019	Gabriel 2013	Organic	Cereals
Smith 2019	Bilsborrow 2013	Organic	Wheat

Table II.A.6: Results of the literature review showing the lower, upper, and average yield effects for a given intervention and crop. Inclusion criteria, and excluded papers and criteria can be found in Supplement B.

Source	Intervention	Crop	Lower	Upper	Mean	n (tests)
Cui 2022	No Till	Wheat	-4.95%	13.64%	3.58%	22
Su 2021	No Till	Wheat	-3.33%	0.09%	-1.42%	3
Su 2021	No Till	Barley	-30.56%	11.88%	-9.16%	12
Pittelkow 2014	No till	Barley	-31%	64%	-2%	59
Pittelkow 2014	No till	Canola	-18%	47%	6%	4
Pittelkow 2014	No till	Oat	-45%	7%	-14%	3
Abdalla 2019	Cover Crops	Oat	-15%	2%	-6%	8
Badgley 2007	Organic	Oat			-15%	1
Badgley 2007	Organic	Wheat	-32%	15%	-9%	2
Badgley 2007	Organic	Beans			-28%	1
Badgley 2007	Organic	Peas			-39%	1
Reiss 2017	Intercropping	Wheat			10%	1
Thapa 2018	Cover Crops	Cereals	-19%	16%	-0.08%	9
Gooding 2007	Intercropping	Wheat	-64%	-25%	-44%	6
Pappa 2011	Intercropping	Barley	47%	50%	48%	2
Bulson 1997	Intercropping	Wheat	-24%	29%		16
Poore 2018	Organic	Wheat	-70%	-13%	-38%	3
Poore 2018	Organic	Maize			-67%	1
Poore 2018	Organic	Barley			-61%	1
Poore 2018	Organic	Sugar beet	-56%	-34%	-45%	2
Poore 2018	Organic	Field beans	-39%	-10%	-24%	2
Poore 2018	Organic	Rapeseed			-65%	1
Conservation Evidence	Alter insecticide use	Barley	-1%	3%	2%	27

Conservation Evidence	Add crop residues	Barley	-0.63	0.23	-0.194	5
Conservation Evidence	Reduced tillage	Grains	0%	0%	16%	1
Conservation Evidence	Reduce chemical inputs	Wheat	5%	8%	7%	2
Smith 2019	Organic	Cereals			-52%	96 (C), 69 (O)
Smith 2019	Organic	Wheat	-26%	-19%	-23%	8

II.4 Practice definitions

Table II.7: Definitions of practices included in the literature review

Practice	Definition
No/Low Till	A method of sowing seeds that seeks to minimize disturbance of the soil to minimize erosion
Organic	Crops: Avoiding or minimizing the use of synthetic fertilizers and pesticides Animal Products: Avoiding or minimizing antibiotics and hormones, generally higher standard of animal welfare
Cover Crops	Crops planted over the winter to prevent soil erosion and nitrogen leakage
Intercropping	Growing two or more crops simultaneously on a piece of land. For example, planting clover with a cash crop can reduce the need for nitrogen fertilizers
Alter Insecticide Use	Reducing or eliminating synthetic pest control chemicals
Crop Residues	Leaving harvest residues post-harvest (or applying residues from an external source) to build or maintain soil carbon (though the extent of these effects is disputed)
Reduce Chemical Inputs	Minimize application of synthetic fertilizers and pesticides (though not necessarily eliminate)

II.5 A note on no-till outliers

UK data on no-till as a farming practice shows a wide range of possible yield effects from a loss of 45% to a gain of 60%. Out of the 104 data points included (the practice with the next greatest amount of data points has 24), 7 are outliers. These abnormalities prompted additional digging so as to understand the reasons for this wide range.

Over half of these data points (and all 7 outliers) come from a 2014 meta-analysis by Pittelkow et al. Most of the studies conducted in the UK that we extracted from this meta-analysis were conducted in the 1980's and 90's. Thus, there is a question of whether these studies are relevant 40 years later, or whether they should be repeated using more modern technologies.

Age of the studies alone, however, is not sufficient to explain the anomalies. Upon closer inspection of each study that contained outliers, the other factors at play become clear. We include a discussion of these no-till studies from Pittelkow et al. (2014) to urge caution in the interpretation of the possible benefits (or drawbacks) of shifting to no-till.

The two outliers showing significant barley yield gains due to no till from Campbell et al. (1986) possibly occur because tillage is not the only independent variable in the study. The three-year study also assessed the effects of the number of times a tractor passes over the fields. While most no-till fields in years 0, 1, and 2 saw slight yield losses, the final no-till year saw significant yield gains relative to conventional tillage, but only in the instances where a tractor passes over the field 5 or 6 times. The author offers the explanation that higher numbers of tractor wheel passes reduces the integrity of soil structure for conventionally tilled fields. Thus, it is difficult to determine whether the yield effects are due to the number of wheel passes, or the choice of tillage.

Christian and Bacon (1990) conducted three long-term studies on no-till production of rapeseed in the 1970's and 80's. Two of the three studies found moderate declines in yield from no-till, while the third found a significant (47%) yield gain relative to conventional tillage. However, the authors explain that, at that site, the conventional tillage plots experienced a slug infestation, which resulted in lower yields. Based on this study alone, it is not possible to determine whether the tillage type had any effect on susceptibility to pests. Therefore, this outlier may mislead interpretations of the results if taken outside of the context of the study.

The largest yield gain (64%) comes from a 25 year-long study, the longest by far included in the meta-analysis (Soane and Ball, 1998). The authors do not offer an explanation for this anomaly, but they do note that *most* years in the study saw yield losses for no-till relative to conventional tillage. They also include a discussion of how long-term success for no-till depends on the burning of crop residues. Most other studies included in Pittelkow et al. burned the residue, with the exception of this one. It is therefore important to note that residue burning as a management practice is not done in the UK today, bringing into question the potential for long-term benefits of no-till for crop yields.

Two outliers showed yield losses from no-till compared to conventional tillage. Newton et al. (2012)'s five-year study on barley investigated the combined effects of tillage, cultivar mixtures, and nitrogen application levels. Across the five years for all treatment types, conventional tillage yields steadily increased (with the exception of a drastic dip in year 3), while the yields for no-till steadily decreased. The authors explain that cultivar and nitrogen treatments significantly impacted yields.

The second yield-loss outlier comes from a 1986 study by Cannell et al. on oat production. This paper consists of two three-year experiments, both of which resulted in a yield loss for no-till compared with conventional tillage. However, the authors offer that the outlier (45% yield loss) can be explained by the additional controlled variable of drainage. In one of the two experiments, drainage was reduced, which affected the yield of the no-till plots but had little effect on the conventionally tilled plots.

The deep-dive on the outliers of no-till studies shows that, not only is there very little data from the 21st century on the yield effects of farming practices (specifically no-till) in the UK, but there are also few studies that look exclusively at the effects of tillage without some additional experimental variables such as nitrogen application or drainage level. Furthermore, for long-term studies containing outliers showing yield gains (such as Soane and Ball, 1998), the extreme values in one direction may dilute the overall trend in the opposite direction.

To conclude, due to the lack of availability of data that focus exclusively on no-till, and that is relevant to today's farming practices, we recommend caution in interpreting the results of our calculator for no-till scenarios. The number of outliers suggests uncertainty for possible outcomes for farms shifting to no-till today.

II.6 Other crop practice examples

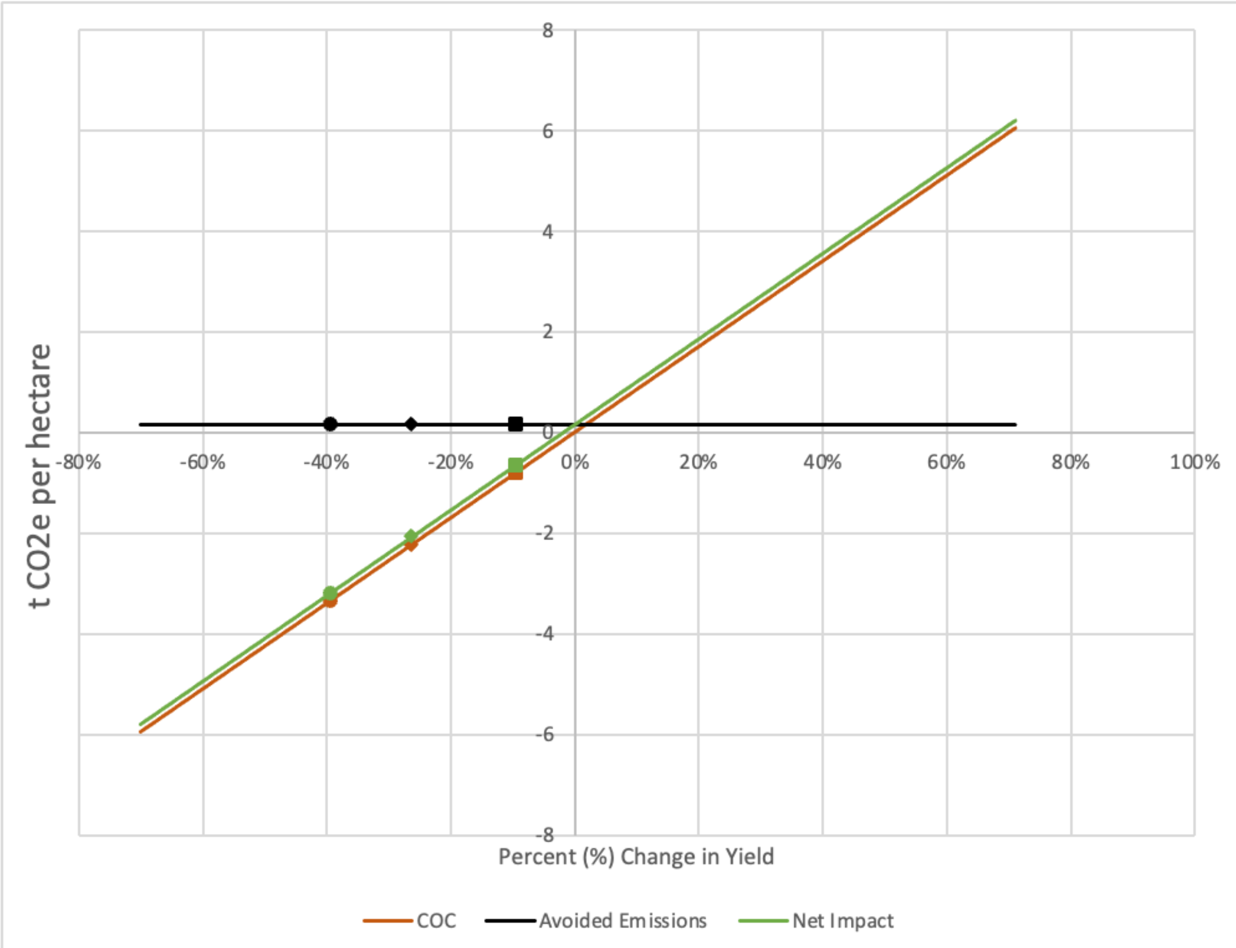

Figure II.1: Shift from conventional to organic production of beans and peas, assuming a 50% decrease in on-farm emissions

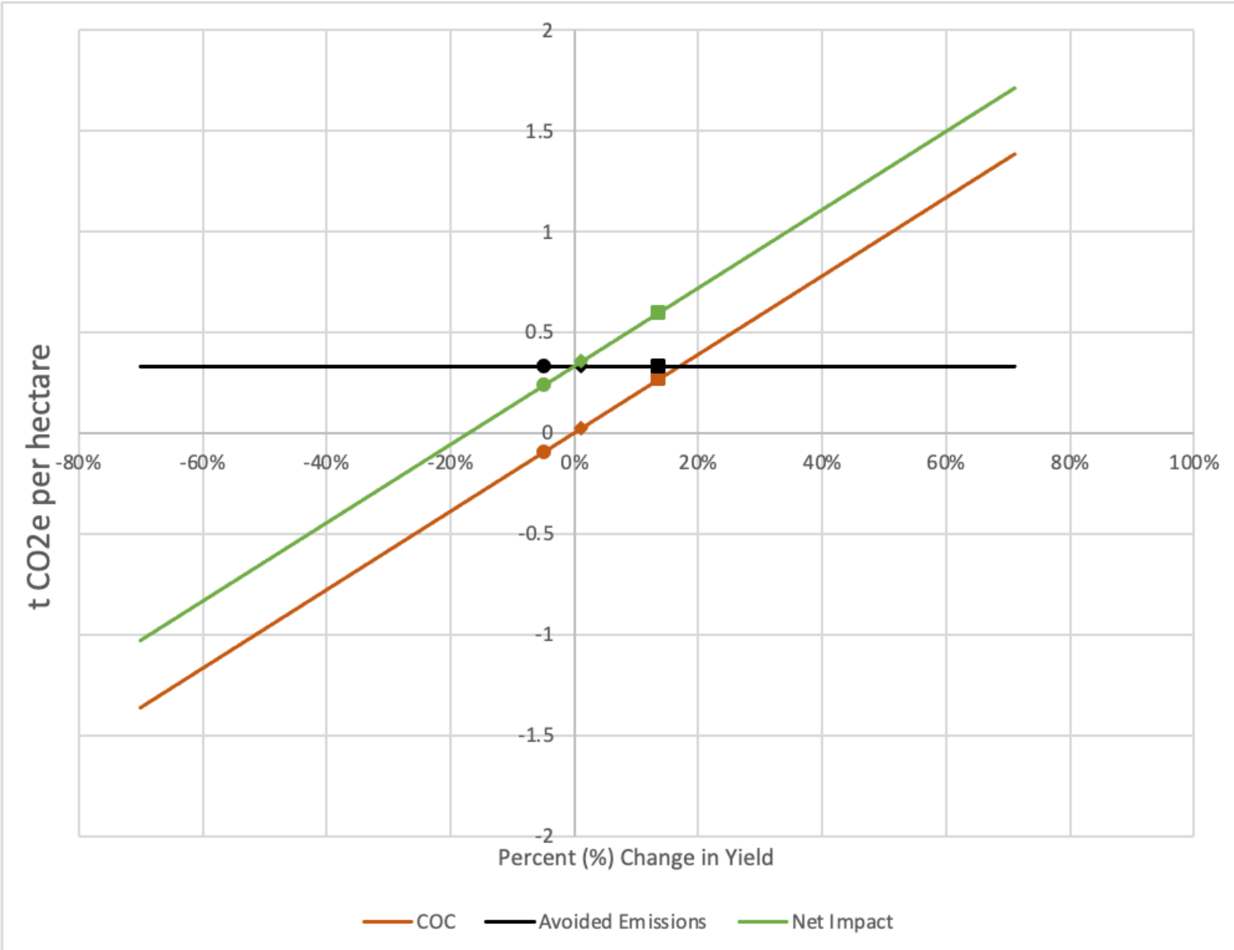

Figure II.2: Shift to no-till wheat production, assuming a 20% decrease in on-farm emissions

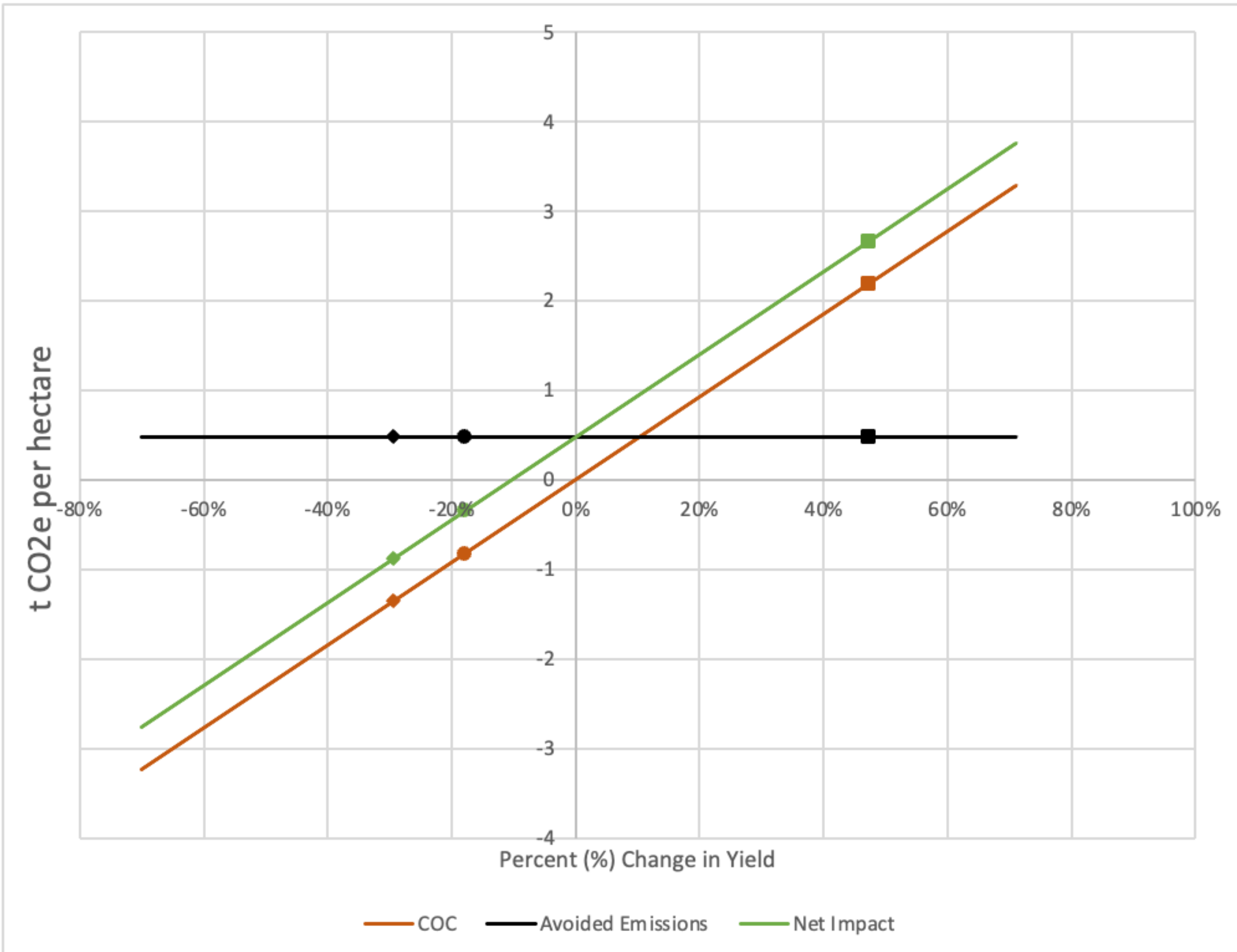

Figure II.3: Shift from conventional to organic rapeseed, assuming a 30% decrease in on-farm emissions.

II.7 Sensitivity of the discount rate for crop interventions

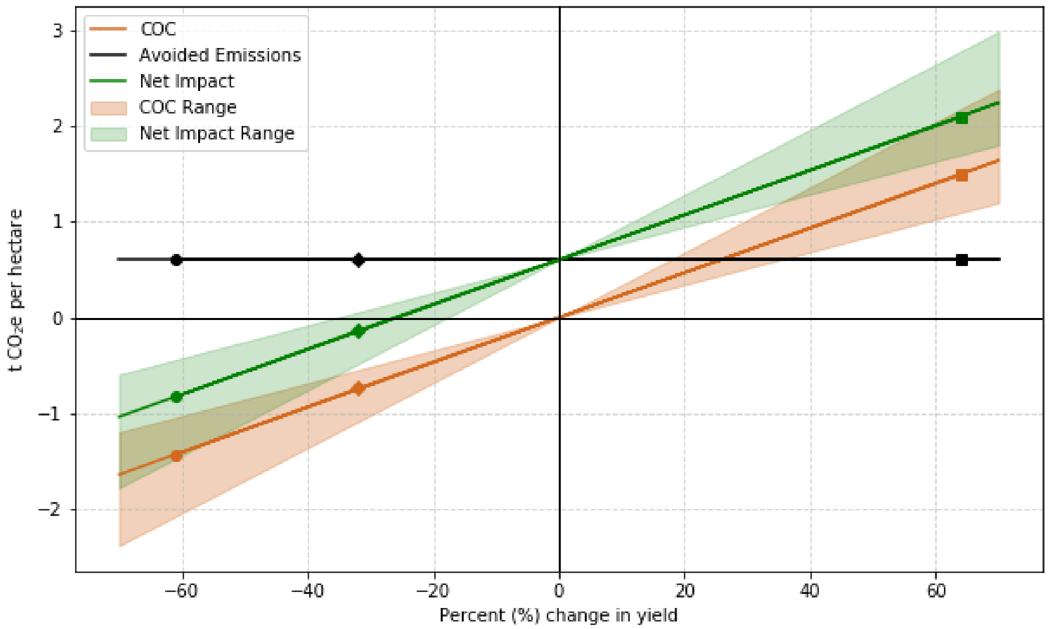

Figure II.4: Effect of applying a discount rate range from 2-6% where the solid red line represents a 4% discount rate for the example in Figure 4 of the main text (organic barley). Organic production shifts from being a net positive to net negative beyond a yield loss of about 25% (approximately the average value). The range of discount rates gives a range of inflection from a yield loss of 18-35%.

Supplement B

Study Inclusion Criteria
Only UK-based studies relating to the yield effects of the following practices are included: organic, no-till, cover crops, crop residue application, insecticide management
1. Peer reviewed journals, PhD thesis, ISO compliant reports, databases or proceedings
2. Report results not presented in another study
3. Assess feed products for animal agriculture (cereals, sugarbeet, canola, beans, peas, maize)
4. Includes values clearly related to the UK
5. Includes yields between BOTH conventional and conservation practices
6. Data is accessible

Studies Excluded

Study	Criteria Not Met	Note	Full Reference
de la Cruz et al (2023)	6	Data requested, no response	Cruz, Vera Ysabel V. de la, Tantriani, Weiguo Cheng, and Keitaro Tawaraya. 2023. "Yield Gap between Organic and Conventional Farming Systems across Climate Types and Sub-Types: A Meta-Analysis." Agricultural Systems 211 (October):103732. https://doi.org/10.1016/j.agsy.2023.103732.
Knapp et al (2018)	2, 4	The UK-relevant data are already included	Knapp, Samuel, and Marcel G. A. van der Heijden. 2018. "A Global Meta-Analysis of Yield Stability in Organic and Conservation Agriculture." Nature Communications 9 (1): 3632. https://doi.org/10.1038/s41467-018-05956-1.
Seufert et al (2012)	4		Seufert, Verena, Navin Ramankutty, and Jonathan A. Foley. 2012. "Comparing the Yields of Organic and Conventional Agriculture." Nature 485 (7397): 229–32. https://doi.org/10.1038/nature11069.
Kirchmann (2019)	4		Kirchmann, Holger. 2019. "Why Organic Farming Is Not the Way Forward." Outlook on Agriculture 48 (1): 22–27. https://doi.org/10.1177/0030727019831702.
de Ponti et al (2012)	6		Ponti, Tomek de, Bert Rijk, and Martin K. van Ittersum. 2012. "The Crop Yield Gap between Organic and Conventional Agriculture." Agricultural Systems 108 (April):1–9. https://doi.org/10.1016/j.agsy.2011.12.004.

Pittelkow et al (2015)	2	Same data as Pittelkow et al (2014)	Pittelkow, Cameron M., Bruce A. Linquist, Mark E. Lundy, Xinqiang Liang, Kees Jan van Groenigen, Juhwan Lee, Natasja van Gestel, Johan Six, Rodney T. Venterea, and Chris van Kessel. 2015. "When Does No-till Yield More? A Global Meta-Analysis." Field Crops Research 183 (November):156–68. https://doi.org/10.1016/j.fcr.2015.07.020.
Shakoor et al (2021)	6	Data requested, no response	Shakoor, Awais, Muhammad Shahbaz, Taimoor Hassan Farooq, Najam E. Sahar, Sher Muhammad Shahzad, Muhammad Mohsin Altaf, and Muhammad Ashraf. 2021. "A Global Meta-Analysis of Greenhouse Gases Emission and Crop Yield under No-Tillage as Compared to Conventional Tillage." Science of The Total Environment 750 (January):142299. https://doi.org/10.1016/j.scitotenv.2020.142299.
Cooper et al (2016)	6	Data requested, no response	Cooper, Julia, Marcin Baranski, Gavin Stewart, Majimcha Nobel-de Lange, Paolo Bàrberi, Andreas Fließbach, Josephine Peigné, et al. 2016. "Shallow Non-Inversion Tillage in Organic Farming Maintains Crop Yields and Increases Soil C Stocks: A Meta-Analysis." Agronomy for Sustainable Development 36 (1): 22. https://doi.org/10.1007/s13593-016-0354-1.
Francaviglia et al (2020)	4		Francaviglia, Rosa, Jorge Álvaro-Fuentes, Claudia Di Bene, Lingtong Gai, Kristiina Regina, and Eila Turtola. 2020. "Diversification and Management Practices in Selected European Regions. A Data Analysis of Arable Crops Production." Agronomy 10 (2): 297. https://doi.org/10.3390/agronomy10020297.
Han et al (2017)	4		Han, Zhen, M. Todd Walter, and Laurie E. Drinkwater. 2017. "N2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-Based and Ecologically-Based Nutrient Management Strategies." Nutrient Cycling in Agroecosystems 107 (3): 335–55. https://doi.org/10.1007/s10705-017-9836-z.
Bulan et al (2015)	4		Bulan, Mary T. Saunders, David E. Stoltenberg, and Joshua L. Posner. 2015. "Buckwheat Species as Summer Cover Crops for Weed Suppression in No-Tillage Vegetable Cropping Systems." Weed Science 63 (3): 690–702. https://doi.org/10.1614/WS-D-14-00088.1.
Mahal et al (2018)	4		Mahal, Navreet K., Michael J. Castellano, and Fernando E. Miguez. 2018. "Conservation Agriculture Practices Increase Potentially Mineralizable Nitrogen: A Meta-Analysis." Soil Science Society of America Journal 82 (5): 1270–78. https://doi.org/10.2136/sssaj2017.07.0245.
Marcillo et al (2017)	4		Marcillo, G. S., and F. E. Miguez. 2017. "Corn Yield Response to Winter Cover Crops: An Updated Meta-Analysis." Journal of Soil and Water Conservation 72 (3): 226–39. https://doi.org/10.2489/jswc.72.3.226.
Quemada et al (2013)	4		Quemada, M., M. Baranski, M. N. J. Nobel-de Lange, A. Vallejo, and J. M. Cooper. 2013. "Meta-Analysis of Strategies to Control Nitrate Leaching in Irrigated Agricultural Systems and Their Effects on Crop Yield." Agriculture, Ecosystems & Environment 174 (July):1–10. https://doi.org/10.1016/j.agee.2013.04.018.
Tonitto et al (2006)	4		Tonitto, C., M. B. David, and L. E. Drinkwater. 2006. "Replacing Bare Fallows with Cover Crops in Fertilizer-Intensive Cropping Systems: A Meta-Analysis of Crop Yield and N Dynamics." Agriculture, Ecosystems & Environment 112 (1): 58–72. https://doi.org/10.1016/j.agee.2005.07.003.
Doring et al (2015)	5	Data relates to yield variability rather than yield	Döring, Thomas F., Paolo Annicchiarico, Sarah Clarke, Zoë Haigh, Hannah E. Jones, Helen Pearce, John Snape, Jiasui Zhan, and Martin S. Wolfe. 2015. "Comparative Analysis of Performance and Stability among Composite Cross Populations, Variety Mixtures and Pure Lines of Winter Wheat in Organic and Conventional Cropping Systems." Field Crops Research 183 (November):235–45. https://doi.org/10.1016/j.fcr.2015.08.009.

Stanhill (1990)	4		Stanhill, G. 1990. "The Comparative Productivity of Organic Agriculture." Agriculture, Ecosystems & Environment 30 (1): 1–26. https://doi.org/10.1016/0167-8809(90)90179-H.
Hossard et al (2016)	6	Appendix links not functional	Hossard, Laure, David W. Archer, Michel Bertrand, Caroline Colnenne-David, Philippe Debaeke, Maria Ernfors, Marie-Helene Jeuffroy, et al. 2016. "A Meta-Analysis of Maize and Wheat Yields in Low-Input vs. Conventional and Organic Systems." Agronomy Journal 108 (3): 1155–67. https://doi.org/10.2134/agronj2015.0512.
Palmer et al (2013)	3		Palmer, Mike W., Julia Cooper, Catherine Tétard-Jones, Dominika Średnicka-Tober, Marcin Barański, Mick Eyre, Peter N. Shotton, et al. 2013. "The Influence of Organic and Conventional Fertilisation and Crop Protection Practices, Preceding Crop, Harvest Year and Weather Conditions on Yield and Quality of Potato (Solanum Tuberosum) in a Long-Term Management Trial." European Journal of Agronomy 49 (August):83–92. https://doi.org/10.1016/j.eja.2013.03.004.

Meta-Analysis?	Studies Included
	Abdalla, Mohamed, Astley Hastings, Kun Cheng, Qian Yue, Dave Chadwick, Mikk Espenberg, Jaak Truu, Robert M. Rees, and Pete Smith. 2019. “A Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity.” Global Change Biology 25 (8): 2530–43. https://doi.org/10.1111/gcb.14644.
*	Badgley, Catherine, Jeremy Moghtader, Eileen Quintero, Emily Zakem, M. Jahi Chappell, Katia Avilés-Vázquez, Andrea Samulon, and Ivette Perfecto. 2007. “Organic Agriculture and the Global Food Supply.” Renewable Agriculture and Food Systems 22 (2): 86–108. https://doi.org/10.1017/S1742170507001640.
	Ball, B. C., M. F. O’Sullivan, and R. W. Lang. 1985. “Cultivation and Nitrogen Requirement for Winter Barley as Assessed from a Reduced-Tillage Experiment on a Brown Forest Soil.” Soil and Tillage Research 6 (2): 95–109. https://doi.org/10.1016/0167-1987(85)90009-1.
	Bilsborrow, Paul, Julia Cooper, Catherine Tétard-Jones, Dominika Średnicka-Tober, Marcin Barański, Mick Eyre, Christoph Schmidt, et al. 2013. “The Effect of Organic and Conventional Management on the Yield and Quality of Wheat Grown in a Long-Term Field Trial.” European Journal of Agronomy 51 (November):71–80. https://doi.org/10.1016/j.eja.2013.06.003.
	Campbell, D. J., J. W. Dickson, B. C. Ball, and R. Hunter. 1986. “Controlled Seedbed Traffic after Ploughing or Direct Drilling under Winter Barley in Scotland, 1980–1984.” Soil and Tillage Research, Reduced Tillage - Rational Use in Sustained Production, III, 8 (November):3–28. https://doi.org/10.1016/0167-1987(86)90320-X.
	Cannell, R.Q., Christian, D.G., Henderson, F.K.G., 1986. A study of mole drainage with simplified cultivations for autumn-sown crops on a clay soil. IV. A comparison of direct drilling and mouldboard ploughing on drained and undrained land on root and shoot growth, nutrient uptake and yield. Soil Tillage Res. 7, 251-272.
	Catt, J.A., K.R. Howse, D.G. Christian, P.W. Lane, G.L. Harris, and M.J. Goss. 1998. “Strategies to Decrease Nitrate Leaching in the Brimstone Farm Experiment, Oxfordshire, UK, 1988–1993: The Effects of Winter Cover Crops and Unfertilised Grass Leys.” Plant and Soil 203 (1): 57–69. https://doi.org/10.1023/A:1004389426718.
*	CE. 2024. “Conservation Evidence - Site.” Conservation Evidence. 2024. https://www.conservationevidence.com/.
	Christian, D. G., and E. T. G. Bacon. 1990. “A Long-Term Comparison of Ploughing, Tine Cultivation and Direct Drilling on the Growth and Yield of Winter Cereals and Oilseed Rape on Clayey and Silty Soils.” Soil and Tillage Research 18 (4): 311–31. https://doi.org/10.1016/0167-1987(90)90117-V.
*	Cui, Yufei, Weiwei Zhang, Yun Zhang, Xinmei Liu, Ye Zhang, Xiaoying Zheng, Ji Luo, and Junliang Zou. 2022. “Effects of No-till on Upland Crop Yield and Soil Organic Carbon: A Global Meta-Analysis.” Plant and Soil, December. https://doi.org/10.1007/s11104-022-05854-y.
	Gabriel, Doreen, Steven M. Sait, William E. Kunin, and Tim G. Benton. 2013. “Food Production vs. Biodiversity: Comparing Organic and Conventional Agriculture.” Journal of Applied Ecology 50 (2): 355–64. https://doi.org/10.1111/1365-2664.12035.
	Giannitsopoulos, M. L., P. J. Burgess, and R. J. Rickson. 2019. “Effects of Conservation Tillage Systems on Soil Physical Changes and Crop Yields in a Wheat–Oilseed Rape Rotation.” Journal of Soil and Water Conservation 74 (3): 247–58. https://doi.org/10.2489/jswc.74.3.247.

Jenkinson, D. S., N. J. Bradbury, and K. Coleman. 1994. “How the Rothamsted Classical Experiments Have Been Used to Develop and Test Models for the Turnover of Carbon and Nitrogen in Soil.” In , edited by A. E. Johnston and R. A. Leigh, 117–38. CABI International, Wallingford, Oxon (CABI). https://repository.rothamsted.ac.uk/item/870q9/how-the-rothamsted-classical-experiments-have-been-used-to-develop-and-test-models-for-the-turnover-of-carbon-and-nitrogen-in-soil.

Lillywhite, R., Chandler, D., Grant, W., Lewis, K., Firth, C., Schmutz, U., and Halpin, D. (2007). Environmental Footprint and Sustainability of Horticulture (including Potatoes) – A Comparison with other Agricultural Sectors. Final report produced for the Department for Environment, Food and Rural Affairs. University of Warwick

Linzell, Brigitte S., and D. S. Madge. 1986. “Effects of Pesticides and Fertilizer on Invertebrate Populations of Grass and Wheat Plots in Kent in Relation to Productivity and Yield.” Grass and Forage Science 41 (June):159–74. https://doi.org/10.1111/j.1365-2494.1986.tb01800.x.

McGRATH, P. F., and J. S. Bale. 1990. “The Effects of Sowing Date and Choice of Insecticide on Cereal Aphids and Barley Yellow Dwarf Virus Epidemiology in Northern England.” Annals of Applied Biology 117 (1): 31–43. https://doi.org/10.1111/j.1744-7348.1990.tb04192.x.

Newton, A. C., D. C. Guy, A. G. Bengough, D. C. Gordon, B. M. McKenzie, B. Sun, T. A. Valentine, and P. D. Hallett. 2012. “Soil Tillage Effects on the Efficacy of Cultivars and Their Mixtures in Winter Barley.” Field Crops Research 128 (March):91–100. https://doi.org/10.1016/j.fcr.2011.12.004.

Pittelkow, Cameron M., Xinqiang Liang, Bruce A. Linquist, Kees Jan van Groenigen, Juhwan Lee, Mark E. Lundy, Natasja van Gestel, Johan Six, Rodney T. Venterea, and Chris van Kessel. 2015. “Productivity Limits and Potentials of the Principles of Conservation Agriculture.” Nature 517 (7534): 365–68.

* https://doi.org/10.1038/nature13809.

Poore, J., and T. Nemecek. 2018. “Reducing Food’s Environmental Impacts through Producers and Consumers.” Science 360 (6392).

* https://ora.ox.ac.uk/objects/uuid:b0b53649-5e93-4415-bf07-6b0b1227172f.

Quinton, J.n., and J.a. Catt. 2004. “The Effects of Minimal Tillage and Contour Cultivation on Surface Runoff, Soil Loss and Crop Yield in the Long-Term Woburn Erosion Reference Experiment on Sandy Soil at Woburn, England.” Soil Use and Management 20 (3): 343–49. https://doi.org/10.1111/j.1475-2743.2004.tb00379.x.

Rahn, C. (Clive), G. D. Bending, Robert Lillywhite, and Mary K. Turner. 2009. “Co-Incorporation of Biodegradable Wastes with Crop Residues to Reduce Nitrate Pollution of Groundwater and Decrease Waste Disposal to Landfill.” *Soil Use and Management* Vol.25 (No.2): 113–23.

Sharma, R. B. 1985. “Plant-Water Relations, Crop Growth and Grain Yield of Spring Barley in Relation to Tillage Methods.” Soil and Tillage Research 6 (2): 111–21. https://doi.org/10.1016/0167-1987(85)90010-8.

Smith, Laurence G., Guy J. D. Kirk, Philip J. Jones, and Adrian G. Williams. 2019. “The Greenhouse Gas Impacts of Converting Food Production in England and Wales to

* Organic Methods.” Nature Communications 10 (1): 4641. https://doi.org/10.1038/s41467-019-12622-7.

Soane, B. D, and B. C Ball. 1998. “Review of Management and Conduct of Long-Term Tillage Studies with Special Reference to a 25-Yr Experiment on Barley in Scotland.” Soil and Tillage Research 45 (1): 17–37. https://doi.org/10.1016/S0167-1987(97)00070-6.

Su, Yang, Benoit Gabrielle, and David Makowski. 2021. “A Global Dataset for Crop Production under Conventional Tillage and No Tillage Systems.” Scientific Data 8 (1):
* 33. https://doi.org/10.1038/s41597-021-00817-x.

Thapa, Resham, Steven B. Mirsky, and Katherine L. Tully. 2018. “Cover Crops Reduce Nitrate Leaching in Agroecosystems:A Global Meta-Analysis.” Journal of
* Environmental Quality 47 (6): 1400–1411. https://doi.org/10.2134/jeq2018.03.0107.

Trewavas, Anthony. 2004. “A Critical Assessment of Organic Farming-and-Food Assertions with Particular Respect to the UK and the Potential Environmental Benefits of No-till Agriculture.” Crop Protection 23 (9): 757–81. https://doi.org/10.1016/j.cropro.2004.01.009.

Tzilivakis, J., Warner, D. J., May, M., Lewis, K. A., & Jaggard, K. (2005). An assessment of the energy inputs and greenhouse gas emissions in sugar beet (*Beta vulgaris*) production in the UK. Agricultural Systems, 85(2), 101-119.

Williams, A. G., Audsley, E., & Sandars, D. L. (2010). Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. International Journal of Life Cycle Assessment 15, 855-868.

Williams, A. G., Audsley, E., & Sandars, D.L. (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report. Defra Research Project IS0205. Cranfield University, Bedford.

Wiltshire, J., Wynn, S., Clarke, J., Chambers, B., Cottrill, B., Drakes, D., ... & Foster, C. (2009). Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food. Defra, London.

Appendix III

This Appendix contains Supplementary Materials for Paper 3 (Chapter 6)

Table III.1 Summary of each high-level theme that resulted from the inductive thematic analysis, and the codes classified under each theme.

Theme	Codes	Summary
Definitions of Sustainability	Agroecology, global versus local, organic, sustainable intensification, trade-offs	Factors contributing to stakeholder definitions of a sustainable ruminant sector, such as the type of production system and the spatial boundary considered
Economy	Brexit, cost of mitigation, economic value of farming, farm viability, imports, incentives, market regulation, other sectors, profitability, tax	The role of ruminant agriculture in the economy and the effects of the economy on ruminant production, including where financial responsibility lies, the implications of certain economic policies, and factors affecting financial decision-making such as profitability
Emissions Reporting	Corporate reporting, eco-labels, farm reporting, metric choice, national reporting	Perspectives on how different entities report emissions at the corporate, farm, and national scales, including consideration of metric choice, spatial boundary, and data availability
Goals and Opportunities	Alternative proteins, animal welfare, beyond GHGs, circular economy, collaboration, efficiency, exporting good practice, food security, peatlands, renewables, resilience, soil carbon, technology, value of land, visions of the future, working with farmers	Views on a wide range of options that would help minimize agricultural emissions, or improve ruminant production against a more holistic definition of sustainability beyond GHGs
Methane	Feed additives, GWP*	Stakeholder views on the potential for technological interventions to reduce methane, thoughts towards novel GHG metrics that consider the short-lived properties of methane, and views towards methane mitigation more broadly
Net Zero	Biogenic carbon, definitions, offsets, reliance on removals, setting land aside	Considerations of how net zero is defined in terms of which emissions sources are included, which Scopes are included,

		as well as the role of offsets and removals, and the value of setting land aside for carbon sequestration
Obstacles	Allocation of removals, beef versus dairy, effectiveness of interventions, fairness, grazing obstacles, hard to abate, land use competition, leakage, overpopulation, permanence of removals, policy instability, public acceptance, reliance on technology, verification	Perspectives on the significance of a number of technological, physical, political, and social obstacles to decarbonizing ruminant production
Perception of Farmers	Cultural value, public goods, reduce farming, role of farmers in society	A range of the ways in which farmers are (or are not) valued by society, such as for their cultural, economic, or social contributions
Reduced Production	Herd reductions, shifting diets	The extent to which stakeholders feel that measures that would reduce ruminant production are needed
Residual Emissions	N/A	How emissions that cannot be technologically eliminated should be addressed, or thoughts on whether agricultural emissions should be required to reach (net) zero
Role of Livestock	Critical of livestock, impact of livestock, in the Global South, livestock is good, livestock is a natural process, nutritional value	A range of views towards livestock in general, ranging from views that livestock production should be reduced or eliminated to those who feel ruminants are nutritionally or ecologically valuable
Supply Chains	Certifications, consumer choice, deforestation, emissions data, role of processors, role of producers, role of retailers, supply chain traceability	Perspectives mostly from corporate stakeholders on how they approach data collection and reporting across their supply chain, including views on what roles different actors within the supply chain should play
Winners and Losers	N/A	Views on who would benefit from certain measures or interventions, and how to ensure a more fair transition to net zero

Table III.2 Quotes for the stakeholder mapping exercise shown in Table 3

CO-CO	If we can discuss with our suppliers in the value chain to set some common targets that we can achieve together, but the challenge is that as long as we are part of this fierce competition on the retail market, it's going to be more or less on a volunteer basis unless

	you get some external factors like policies that supports that we need to commit to certain standards. - DK.CO.05 They don't want to tell everybody if they've got a kind of a competitive advantage or they are showing they don't want to say we've reduced our emissions and we've reduced our emissions and here's how They'll tell the customer, the retailer. But they won't necessarily want to divulge it to their competitors. – UK.CO.02
CO-FA	[Farmers are] not running a charity. They need to make money. They need to be able to have a good life … and if they're being asked to invest, there has to be a return on that investment, and often they can't see what that return is. - UK.CO.02 I wouldn't expect the farmers to be as engaging with sustainable practices and actually, I think, the way to crack it is actually demonstrating to these farmers that they're doing a lot of these things already, they just don't realize they're doing it. You know, there's things that's contributing towards being more sustainable that they don't consider. Because they're not doing it to be sustainable, if that makes sense. They're gonna be doing it for money, or whatever. But it's actually breaking down that barrier in terms of the knowledge that they have around sustainability. – IE.CO.01 So in the transition of the farmer, it's not just moving from one type of fuel to another type of you know this really has a mindset change as well. Secondly, there's a lot of focus on the on the feed obviously. [Feed additives] is an intervention that we're doing with the farmers who are open to that, we do not impose anything to our farmers. We provide options. – NL.CO.04
CO-GO	So we are confronted with policymakers, for instance, of the European Union. They say we have signed the Paris Agreement. And that means you have to report to us your carbon footprint. And you do it in this in this format which is relevant for Paris Agreement. Then the European Commission comes and says OK. We have developed CSRD. And into CSRD you have to do life cycle analysis. So you have to report within CSRD according to life cycle and analysis. And that's totally different than what we have to report in the Paris Agreement. While that's only your local footprint and that has nothing to say. – NL.CO.02

	The farming 25 year road map green energy transition CCC 7th assessment report. All of which could be deemed as an effort to restrict livestock numbers, thereby driving up the cost of meat and reducing consumption. -UK.CO.02
CO-RE	I don't even want to discuss with [green NGOs], because there's a fact that says that the demand for protein, animal protein, will rise with between 20 and 30% So if we lower the animal production in Denmark or Europe, we'll just get the animal production from South America. -DK.CO.03
FA-CO	And then we have young lads. He was born with horses, and he went to a dairy farm, and he's now a tillage advisor. I go *hmm*, there's no tillage in his background whatsoever. He might have spent six months going around, looking at places, yeah, right, and then I'm to ring him, asking him about crops? – IE.FA.02
FA-FA	Well, I think we have three types of farmers. We have in front runners, we have the big middle group, and then I shouldn't call them losers, people who are close to not caring, and they are not considered. They don't care so much, they just want to quit some time and get out of the business as best as possible. – DK.FA.02 So it kind of gets back to this remit of farmers are delivering multiple public goods on behalf of the nation. So as well as affordable, nutritious food, you know, we're asking them to reduce emissions but increase carbon storage and improve water quality and stop water flooding our homes and increase biodiversity. And all make the landscape nice. – UK.FA.01
FA-GO	The government is now not really supporting entrepreneurship. So many farms got a permit to build a barn, but then the court rejected those permits… –NL.FA.02 We're done with ELMS, we've done with SFI rubbish and you know, spent all the money because all the well heeled land owners got their agents to milk the system. And a lot of genuine farmers missed out. –UK.FA.03 And it's, of course, very difficult, because you can sit here in Copenhagen and be in dialog with the authorities and the NGO on environment and find a solution and the farmers. He's, of course, not involved. – DK.FA.01

FA-RE	[NGOs] always talk positive about the farmer, because the farmer, he tries to do his best, but he's ended in a situation with a too big farm, after their opinion, and farm with too much pressure on the environment. But if you look at some of the small groups, which are very they are attacking in the media, even they go into the farm, take videos of the production and try to make stories about how bad an industry it is and that we should stop that kind of farming we have at Denmark. – DK.FA.01 All of a sudden we've got ELMs, which is, you know basically, run by NGOs, you know, I mean it was the test and trial projects that created the options under ELMs were not funded by government. So they were dependent on well funded organizations like National Trust like soil association, like RSPB you know you've obviously carved out all these options that favor feeding birds and insects over humans. – UK.FA.03
GO-CO	I suppose we're talking about climate action plans and national targets and global targets for we're focusing on the on, on the headline figures of emission, as opposed to the intensity piece. Yeah, whereas your food producers will maybe focus more on the intensity. – IE.GO.02 I guess the companies, they're not looking at an economy wide target. They're looking at a target within their own business so the sectors can be blurred. – UK.GO.01
GO-FA	Basically you can turn up the CO2 tariffs, you can just turn it up, and then that will reduce the amount of gas. Because then you will basically make it more expensive to be a farmer and then the farms will start closing. And that's basically not a problem for the Danish economy, because the Danish farmers don't make that much money, and they'll get job in other industries. – DK.GO.01 So we don't get involved in that debate because if we did. It would be. Well, what we want to avoid the situation where [government agency] is portrayed as telling the farmers, they have to do this, which is adversarial and counterproductive, much like in the good old days prior to Brexit, say, well, the EU wants us to do this. In fact, it's in our own interest to do this, but we're able to say, well, someone else wants it. So we're trying to avoid that. – IE.GO.01

	So intervening in agriculture has proven to be politically very, very sensitive. So basically, there hasn't been a political majority to do so, or at least to go for those more mandatory policies. – NL.GO.01
GO-GO	So we're not shoving. It might feel like that. That's not our job. To shove something down. It's to work collaboratively and part of setting the sector is what is feasible? – IE.GO.01 But if you want to [change policy], it will take a whole different legal system, which will take five to six years if we can ever implement so you cannot go so fast in policy. – NL.GO.01 We live in a democracy in which successive governments don't like to tell people what to do. It's not just the color of the government. Yeah, they don't really want to do it. They might impose a bit of a tax on things they think are particularly harmful to people. That's about as far as they go. And there certainly wouldn't be any appetite for banning meat or limiting the consumption of meat. – UK.GO.02
GO-RE	And there'll be some academic out of Cambridge who pops up and goes, What about this concept? And we'll be back to where we started. That's a risk for the policymaker. There's so much noise in the system that it delays action. -IE.GO.01
RE-CO	Neutrality in 2050 you know, I remember that this vision came. I think it was in 2019, you know, where [processors] said it [farm interest group] said this and it was just politics, right? It was just to kind of say we go in the green way. We have no idea how to do it. And I guess maybe that's quite common, but I have not seen anybody making concrete plans. – DK.RE.05 I'm not so sure [companies] know how to measure stuff in this. And all of the other companies making claims about this stuff and the other, like what? I mean, yeah, until you can go out and dig a hole and measure the amount of carbon in the soil. If you're not doing that, then it’s speculation. (IE.RE.03) So we don't use [enteric methane inhibitors] commercially, yeah. There has been a pilot feed additives demonstration on a number of commercial farms there in the last year, so winter 2023-24. There is a lot of nervousness within the dairy industry relating to the use of feed additives to reduce emissions. This primarily relates to the impact that mis-

	information about a UK pilot project on feed additives in 2024. Currently milk from these research trials is not accepted for human consumption by Irish dairy co-ops. – IE.RE.04 I discussed this also with people from industry, where I said, you really have to put effort on making your efforts visible, yeah, and your reduction of footprint visible, and also make clear that, hey guys, you won't see it in the national inventory, but you will see it in the footprint of the milk. – NL.RE.01
RE-FA	So you have a situation where, I mean, I would say, if you ask most Danish farmers, like last year, what is your CO two emission per liter of milk, they would know. You would already have had a system where, where you would have calculated this for your farm, but you also have incentives. – DK.RE.01 Farmers are very hesitant to do any investments. Have been for the last couple of years, because they don't know what will happen in five years time. They know that a CO two tax is coming, but farmers have maybe always been criticized, but especially the last 10 years, right? They are to blame for everything. – DK.RE.05 But farmers here, rebellious factions actually within co-ops are now saying, see this sustainability stuff is complete ********. What you're asking us to do? Look at what they're doing in the states. They're just going to produce the milk and they're not going to be held back. – IE.RE.02 What I was seeing was that farmers didn't know where to start. They didn't know what to do. They knew environmental sustainability was important and of course farmers don't want to pollute the planet, they want to become more efficient. – UK.RE.01
RE-GO	National priorities is also doubling the area the organic production, organic farming production and organic farming area, which will reduce productivity and to me, without any very obvious reasons, I mean organic production, as I see it, compared to modern, conventional production in Denmark is not creating so much, let's say environmental benefits so it to me, it doesn't make sense. – DK.RE.03 So when I talk to people in government and issues of metrics comes up they often say “I don’t care what metric is used, we have to start reducing emissions. And that's the real

	challenge…It's now a matter of trying to deliver on [the national strategy], and that needs a whole of government and whole of industry approach to get behind that and go right. We're serious about this. – IE.RE.04 The noise of support from government has not been helpful because it hasn't been connected and it hasn't been clear. – UK.RE.01
RE-RE	On the other hand, as I see it, the public opinion is extremely determined by the green NGOs, in Denmark, what we were usually calling a civil society, it's very, very powerful talking about farming. And that's bit strange to me. – DK.RE.03 And animal agriculture is so controversial for so many other reasons that I see environmental NGOs, for example, who totally reject the GWP* metric because they think it gives a free pass to agriculture missions. And in a sense, they don't like animal agriculture anyway. So this is just another kind of argument that you might use, apart from animal welfare concerns and water quality and so on, to actually limit the size of animal agriculture. – IE.RE.01

Table III.3 Data behind the summaries shown in Figure 1, which illustrates the relationship between views towards GWP and the perceived urgency of ruminant GHG mitigation.*

Quadrant	Quotes
GWP*+, urgent	I think in future when the blame game has been played for climate change, you know [methane] would have to be taken into account. And so GWP star, the role is … to get to a point where you slam on the brakes and stop. End your contribution to global warming as quickly as you can, and GWP star and warming impact studies help you do that. (IE.RE.05) We looked at GWP* quite a lot actually. Ultimately we shied away from using it because we didn't want to introduce a new metric to the system. We were obliged under the under the Act to report using conventional reporting. So to quantify our carbon budgets in terms of GWP 100, which we did… we should always be concerned when we are arguing for something that actually falls in our favor. The reason why we have to be careful, even if it's not conscious in our own pleading and promoting a temperature based approach to climate neutrality, that we aren't doing a bit of special pleading here because the gas that it most impacts is methane and our treatment of methane is directly impacted when if you adopt the temperature approach. I personally don't think we are specially pleading. I think methane should be treated differently because it is different. It is the recognition of that that would allow us to mitigate methane emissions as aggressively as we can. (IE.GO.03) Scientifically, [GWP*] makes a lot more sense, but it makes the accounting somewhat more difficult for policymakers and so on to grapple with, because they would just prefer to have simple conversion factors and so on. (UK.FA.02) Even GWP* at a national level disincentivized mitigation of methane emissions from sectors like agriculture. And put most developing countries at a disadvantage compared to developed countries. And it also says it's more advantageous metric for countries that have large historical methane emissions because it suggests that reducing methane emissions leads to global cooling. (UK.GO.01)

	And equally incentivized reductions at all, you know at the individual farm level, you know, if a farm can demonstrate that is achieving a permanent reduction in the rate of flow and demonstrate and verify are key here. Then they are producing a cooling effect that is, gives the rest of the economy time to adapt if you like, or is a valuable service to the rest of the economy. (UK.FA.04) Having said that, permanent reductions in the flow rate of methane do cause well, let's call it cooling, but they reverse past warming from the methane. So there's still an important lever to pull and I'm not saying we shouldn't reduce methane. We can and we should, because it has an important effect. There's just a balance to be had between good reductions in nitrous oxide and reductions in methane, properly valuing the reductions in methane and recognizing their contribution. (UK.FA.04) So [GWP*] doesn't exactly help us in in that sense, it does, I think put a better light on agriculture if methane as not having as big an impact as it's currently measured to be so Irish agriculture somehow doesn't have a problem. But it does. Don't get me wrong, it does have a problem. (IE.RE.03) Methane obviously has quite a big cooling effect if you reduce emissions, but in Ireland methane emissions increased slightly over the last decade. So for the next 16 years, if we started to reduce emissions tomorrow, we still have the warming effect from this increase, which is primarily associated with the increased number of dairy cows. (IE.RE.04) So I think that the criticism of GWP star is just misguided and it's really not addressing the real issue is that if you look over the full historic period, all developed countries have had a very large contribution to warming and they will need to, even though much of that warming took place in a time where people were not really particularly aware of climate change. But that doesn't really matter because your actions have consequences. (IE.RE.05)

	Ultimately where you start from shouldn't really influence your direction of travel because even if we do have a new methodology, obviously it might dictate slightly different ways of how we get there. (UK.CO.01) I think I can't see how you can use GWP* in corporate reporting or on a product level, that doesn't make sense for me. But if you model on a global level, I think it's the right one. (DK.CO.02) But I'm going to take your point on in your paper, which I think is exactly the point. All metrics are wrong, but some are useful and they tell us different things, and GWP* tells us something different from GWP100 yeah, the heating capacity impact of the gas versus a carbon auditing account. So GWP star has its use but it doesn't give us the end game of removing that that methane which we critically need to do (UK.RE.01) You know, as the world is warming up and GWP star actually emphasizes that we should be doing everything we can to reduce methane (UK.RE.02)
GWP*+, less urgent	Biogenic methane should be accepted as long as we are not expanding, (DK.FA.02) Our grasses can absorb CO2 through the methane cycle (NL.CO.03) Now when I first started thinking about this stuff, which is a good 15 to 20 years ago. I would have said that gives us time to kind of consider what we would do in the longer term. For me, agriculture biogenic methane I think we've lost that time. So for agriculture methane, now is the time to address it as well as all the other forms of methane. And it isn't special pleading. Out to 2030 and even as far as 2040, GWP100 will work fine. It'll create an appropriate enough signal to reduce all the gases involved. Actually, I think it doesn't give you enough of a signal for methane to reduce methane emissions because it underestimates what the reduction of methane would actually achieve in the real world climate. But if you continue the use of GWP 100, beyond that you will be asking more of methane than is necessary to achieve the climate objective… can you achieve net zero seem to net 0 gases with ruminant agriculture? The long answer is no. The shorter answer is

	you can try. And in trying you will be asking the sector which is producing the methane emissions to pay for removals of CO2. And that will not be fair. Because they didn't put the CO2 there. (IE.GO.03) As my understanding is that if we change the accounting change to, say, the end of the, also apply that to the baseline and we still have to make a 30% reduction. So it doesn't exactly help us in in that sense, it does, I think put a better light on if methane is not having as big an impact as it's currently measured to be Irish, agriculture somehow doesn't have a problem. But it does. Don't get me wrong, it does have a problem, but I mean it's not as it doesn't seem as big. (IE.RE.03) You know, even it would be impossible, I think, to hit a net zero GWP 100 net zero greenhouse gas by 2050 without decimating that industry, but. With the temperature neutrality approach you do, it gives you more possibility to keep that industry in fairly healthy state over the next few decades. (IE.RE.05) So we are really excited, really interested in understanding more about that. Certainly for our efficiencies and how that might actually turn the dial from beef is our number one risk area to actually beef is in a really good place. (UK.CO.01) you know we wouldn't be able to [reach net zero] unless of course we could use GWP star to offset our methane. (UK.RE.01) I follow a Northern Ireland farmer on Tiktok. I love him, last year, he did a whole, it could be maybe four or five minutes of a TikTok. And he had all the graphs done and all that. Like what you said about the methane. It's there. It's level. It doesn't change. Why you're blaming the cows for it? It makes no sense. Yeah, so I'd agree. There's no real change. (IE.FA.02)
GWP*-, urgent	We don't want to take the easy route as such if we can find a calculation that makes things look better, then just jumping on that because that's going to have repercussions further down the line. (IE.CO.01)

	To have two farms with same emissions, but providing different carbon footprints, even though it's exactly the same. It's not intuitive, like, you know, opposite to intuitive. And I think it also because with GWP star is the one that has emitted the most and are reduced, will have lower carbon footprint. So it kind of promotes that good to be bad, And that, I think, is wrong. (DK.CO.02) There's a reputational risk about looking to be perceived to pick the more advantageous the balance be picking, the more advantageous definition for your particular circumstances. But maybe that is also the more scientifically robust. (IE.GO.01) GWP* isn't going to be a savior in the short term as it will increase the warming effect associated with the increased methane emissions. It could be really damaging to you, (IE.RE.04) You can use [GWP*] to justify inaction. That would be an abuse of the metric. That's not what is intended to do, I think. When you have vested interests involved in these things is your you hear all kinds of stuff, you know, it's up to policymakers to see through all that and to come to their judgment (IE.RE.05) Well, what's the difference between the GWP* and the GWP 100 because some people also want to add it up. If you would do it at school, your math teacher would really hit you, because the GWP* is a change in an emission rate, whereas a GWP 100 is an emission rate. You can't add them up because they're different units, but many people do because it suits them. (NL.RE.01)
GWP*-, less urgent	None

Table III.4 Quotes from stakeholders regarding their understanding of and feelings towards net zero or sustainability targets more generally

Interviewee	Quote
DK.CO.01	"So step one, reduce all that you can and then, if possible, you can buy some credits somewhere… you can reduce your impact to a certain degree, and then you need to compensate for the rest. In most cases, I do not know of any that can go to net zero without using compensation in some way."
DK.CO.02	"So we want to be fossil free in the value, or as well, is the idea, and then to minimize the rest of the emissions, but again, we will never get to zero, so you need to balance this out in one way or another. And then, of course, that big question is, how do you do that? Because we are one of the few sections I think that can do something in our own value chain, like with carbon sequestration."
DK.CO.04	"Actually, personally I don't like the word climate neutral because I think it's. It's difficult to say, but I don't think it's possible…we are human and we use resources to a lot of things... I don't know what we can do… but neutrality is a big word."
DK.FA.01	"We have it in Denmark for the society as a whole, we have to be neutral in 2050 or 2045 the agriculture will, I think, still have some emissions in 2045 but if we have a lot of pyrolysis, we can do a lot there. So it depends, because we can capture CO_2 from the industry, and we can capture the CO_2 with the nature that could be new forest, or that could be by the annual crops you have, they take up enormous amount of CO_2 but it's going around."
DK.RE.01	"So, net zero emissions means not 0, but it means a certain amount of emission and a certain amount of sequestration"
DK.RE.03	"I mean, it must be that the emissions, we will always have residual emissions, that emissions are balanced with some uptake. It could be in forest. It could be carbon content in agricultural soils, and especially I think that the biochar has potential there, because we can say that the carbon is there and it will stay there"
IE.CO.01	"But yeah, we have our sustainability strategy and that's basically our road map to net zero across our entire business by 2040. And then within that we have like reducing SCOPE 3 emissions intensity…I think it's unlikely that agriculture as a whole will achieve net zero. Let's be realistic, but I think it can contribute towards that net zero target, you know, can reduce direct emissions from farming, increased carbon sequestration through vegetation. And then reduce emissions in other sectors, so like producing renewable energy with solar panels, and things like that."

IE.GO.01	“In in the Irish context, I suppose what we're finding is it doesn't really matter what definition of neutrality in the real world. The level of reduction. How much you have to reduce it's actually get on with reducing is the big sticking point”
IE.GO.03	“Can you achieve net zero with ruminant agriculture? The short answer is no. The long answer is you can try. And in trying you will be asking the sector which is producing the methane emissions to pay for removals of CO2. And that will not be fair. Because they didn't put the CO2 there.”
IE.RE.01	“As I understand it, the Commission is quite explicit that they do not reach a net balance in emissions using the GWP 100 metric by 2050 but their presumption is that CDR technologies would be available to meet that gap. So it's not physically possible anyway to produce food without GHG emissions, but they don't have to go to zero.”
IE.RE.02	“I don't understand what [net zero] actually means for ruminant agriculture, because there will always be emissions. People need food.”
IE.RE.03	“Well, I think net Zero's creative accounting. Full stop. It's an impossibility if we want to exist as humans, we have to get over the fact that we're going to have an impact on the environment. Full stop. Net 0 is certain for corporates to push so they can feel good, you know.”
IE.RE.05	“You know, even it would be impossible, I think, to hit a net zero GWP 100 net zero greenhouse gas by 2050 without decimating that industry, but. With the temperature neutrality approach you do, it gives you more possibility to keep that industry in fairly healthy state over the next few decades.”
NL.CO.01	“I think it's kind of fair to say we are in line with the Paris Agreement. But to be really net zero, you have to have the reductions of, Well, depends on what sector you're in, but 90% reduction and then residuals can be compensated somehow, but it changes every year how it can be compensated.”
NL.CO.02	“I like the ambition. But speaking out an ambition which is. Not reasonable to reach, and also within the future somewhere. You're not there anymore on that position you are now crazy. So, we should not give these people this type of words to use them because you know they are going to use it and do nothing.”
NL.CO.04	“A couple of years ago, [company] was still behind carbon neutrality as one of the elements, but we got feedback and we thought, yeah, this is just not the right concept. Net zero, that is the way to go. It's so relatively new, the whole net zero discretion, there will be many more developments coming and we as [company] are open to this kind of discussion because it's not about us, it's about a proper future of the world. It's about ensuring that we are able to grow crops that we can feed the world population and limit global warming to just one and a half two degrees”
NL.RE.01	“And also the industry aims at net zero, if you look at the goals of [companies], they want to go to net zero in 2050 and 50% reduction already in 2030 but in fact, in agriculture, in fact, in all agricultural systems, you can't go back to zero. So it means that you need also sequestration. Well, some people have very high expectations of sequestrations in pastures.”

UK.FA.01	“We could get to net zero easily. Just don't produce anything… I don't think we should be aiming for every farm to get to net zero. You know, that too is unrealistic.”
UK.FA.02	“But you know you can't cut emissions from economic activity by 100%. You have to cut them as far as you reasonably can, and then you have to look for counterbalancing greenhouse gas removals to set against your unavoidable, resilient emissions… What you have to do is to remove your carbon offsets as rapidly as possible into actual removals, and those could be nature based or engineered. But then given some of the doubts around nature based removals with their additionality and permanence and everything, you need to have a diverse portfolio of greenhouse gas removals.”
UK.GO.01	“You talk about climate neutrality in agriculture, but we don't think that's a possibility because we separate out LULUCF and agriculture. So for us, agriculture is a hard to decarbonize sector and LULUCF is where you have the removals. So it's LULUCF that's going to have increasing importance into the future”
UK.RE.02	“You can get probably more than half of it through farming measures and then the other half has to come from diet change to less carbon intense foods.”

Section A: Filter for CUREC 2 application		
This section determines whether the application for ethics review should be made using this form (CUREC 1A) or the CUREC 2 form (for research with more complex ethical issues).		
Please indicate with an 'X'.	Yes	No
Does the research involve the deception of participants?	☐	☒
Are the research participants vulnerable in the context of the research, or classed as people whose ability to give free and informed consent is in question? For example, Participants aged 16 or under (also answer question A5); Participants aged 16 – 18 (refer to competent youths for guidance); adults at risk; Note the University's Safeguarding Guidance and Code of Practice and its implications for researchers involving young people or adults at risk.	☐	☒
By taking part in the research, will participants be at risk of criminal prosecution or significant harm?	☐	☒
Does your research raise issues relevant to the Counter-Terrorism and Security Act (the Prevent Duty), which seeks to prevent people from being drawn into terrorism? Best Practice Guidance 07 on the Prevent Duty provides further guidance.	☐	☒
If you answered 'No' to all the questions above, go to Section B. If you answered 'Yes' to any question above, continue to question 5 below.		
Is your project covered by a CUREC Approved Procedure?	☐	☐
If yes, list the CUREC Approved Procedure(s) you will follow		
If you have answered 'No' to all questions 1-4, go on to Section B. If you answered 'Yes' to ANY of questions 1-4, and answered 'No' to question 5, stop completing this form and do not submit it for ethical review. You will instead need to submit a CUREC 2 application form. If you answered 'Yes' to any of questions 1-4, and your project is covered by an Approved Procedure, go on to Section B. If more than one Approved Procedure applies, contact the SSH IDREC or your DREC for advice on whether a CUREC 2 form should be submitted instead.		

Section B: Researchers	
Name of Principal Investigator or student's supervisor	Myles Allen
Department or Institute	School of Geography and Environment
University of Oxford email address	Myles.allen@ouce.ox.ac.uk
Copy and paste the following six rows as necessary to complete for each additional researcher who will be involved in this study, including student(s) and those external to the University.	
Name of researcher or student	Jessica Zionts
Department or Institute	School of Geography and Environment
University of Oxford email address	Jessica.zionts@ouce.ox.ac.uk
Role in research	Student
Degree programme, if student research	DPhil
The whole research team	

Have the researchers undertaken research ethics and integrity training?	Yes ☒	No ☐

Please provide details of any research ethics and integrity training undertaken, including the dates of the training. Alternatively state relevant research experience.	Research Integrity: Core Introductory Course completed online in March 2023.
State any conflicts of interest and explain how these will be addressed.	Research is funded by Hilton Food Group, however contract guarantees that the funders may not influence or contribute to the research, and the University maintains all IP. Funding will also be disclosed to all potential interviewees.

Section C: The research project	
Title of the research project	
Perspectives on climate neutrality in the agriculture sector	
Anticipated start date of the aspect of the research project involving human participants and/ or personal data (dd/mm/yy).	24 March, 2025 (approx.)
Anticipated research end date (dd/mm/yy).	20 June, 2025 (approx.)
Provide a brief lay summary of the aims and objectives of the research. This should cover the questions it will answer and any potential benefits. (max 300 words)	
Currently, different stakeholder groups and national policies around the world operate on different assumptions about how to measure and mitigate the impact of agricultural production. These discrepancies result in disjointed efforts and can cultivate perverse incentives. Thus, there is a need to understand the origins of these different assumptions, whether due to political agendas or scientific (mis)understanding to attempt to create a more unified vision of a sustainable food future, and to better delineate the roles that government, industry, and farmers can play. The primary aim of this study is to map stakeholder definitions of climate neutrality and conceptualizations of sustainability in the livestock sector. In line with this aim, we ask the question; how do definitions of climate neutrality in the agriculture sector differ across stakeholder groups and geographies? Are these definitions influenced by what mitigation opportunities are available for a given stakeholder? To do this, we will analyze themes, similarities, and differences across stakeholder perspectives, determine whether it's possible to establish a unified definition for the climate neutrality of livestock. Underpinning these objectives is a more philosophical question about whether the concept of climate neutrality should be relevant at all to the livestock sector or agriculture as a whole. Unlike fossil fuels, which have zero-carbon alternatives, agriculture will never be free of environmental impacts whether that's on climate, land use, biodiversity, or water use. Despite this, humans will always need agriculture. Given this reality, is 'climate neutrality' an appropriate goal to begin with? Or should we seek out an alternative paradigm?	
Please indicate the methods to be used (indicate with an 'X'):	

Analysis of existing records	☒
Snowball sampling (recruiting through contacts of existing participants)	☒
Use of casual or local workers e.g. interpreters (refer to guidance in BPG 01: Researcher safety)	☐
Participant observation	☐
Covert observation	☐
Observation of specific organisational practices	☐
Participant completes questionnaire in hard copy	☐
Participant completes online questionnaire or other online task (refer to guidance in BPG 06: Internet-mediated research)	☐
Using social media to recruit or interact with participants (refer to guidance in BPG 06: Internet-mediated research)	☐
Participant performs paper and pencil task	☒
Participant performs verbal or aural task (e.g. for linguistic study)	☐
Focus group	☐
Interview (refer to guidance in BPG 10: Conducting research interviews)	☒
Audio recording of participant (you will generally need specific consent from participants for this)	☒
Video recording of participant (you will generally need specific consent from participants for this)	☐
Photography of participant (you will generally need specific consent from participants for this)	☐
Others (please specify below)	☐
Provide a brief summary of the research design and methods. What will research participants be asked to do? (max 300 words) Please also submit a copy of the questions participants will be asked, if applicable, or some information about the sorts of topics that will be covered.	
This is a mixed-methods study looking at stakeholder perspectives on what 'climate neutral' agriculture means. The stakeholder groups included are academics, farmers, corporations, and national governments. The study will include stakeholders from New Zealand, the UK, Ireland, and Denmark. These choices were made because stakeholders in these countries are leading the discussion on debates around how to measure and mitigate agricultural impacts. The first step in this study is a discourse analysis of published perspectives on agricultural impact assessment and mitigation. This analysis will be used to create decision tree diagrams for each stakeholder group. A hypothetical example of these diagrams can be found in Appendix 1. These will serve as the basis for the interviews.	

Interview participants will be purposively selected to represent a range of perspectives within each country and stakeholder group. We recognize that these samples will not be representative, but we rather seek to include enough people to encapsulate major differences in opinions. These semi-structured interviews last for about one hour each. They will be no shorter than 30 minutes and no longer than 90 to avoid stakeholder fatigue while still allowing for extra time should a conversation prove to be productive and mutually interesting. We will start by having the participant introduce themselves and provide any initial thoughts on the topic which can be used to build the conversation. They will then be presented with a diagram for their stakeholder group and we will discuss how they relate to it, what they disagree with, and where their views lie across a spectrum. Their responses in this initial phase of the interview will guide the rest of the conversation. These interviews will be recorded and transcribed by hand. The transcriptions will then be thematically coded inductively using NVivo. As the interviews will be semi-structured, there is no pre-determined set of questions. However, we will broadly cover topics around what how the participant defines sustainable agriculture, their thoughts around the use of different greenhouse gas and land use metrics, their assumptions around what constitutes 'climate neutrality,' and the role they see for themselves and other stakeholder groups in achieving the vision of sustainable agriculture as they defined it. A scaffolding of topics to be covered in the interviews can be found in Appendix 3.

List the location(s) where the research will be conducted, including any other countries.	New Zealand, Ireland, Netherlands, Denmark, United Kingdom
Clarify which parts of the research will be conducted in-person and which will take place remotely, e.g. online.	I aim to conduct as many audio recorded interviews in-person as possible. Some may be conducted online if an in-person meeting is not possible.

If your research involves fieldwork or travel and your department requires a travel risk assessment, will you have completed and returned a risk assessment form beforehand? Please indicate with an 'X'. (This must be approved by your department before you travel. If you are travelling overseas, you are advised to take out University travel insurance.) Refer to guidance available from your Department, the Safety Office, the Social Sciences Division, and the Humanities Division, and on travel for University business.	Yes	☒
	No	☐
	Not required in this instance	☐

In the case of international or collaborative research, explain how you will address any ethical issues specific to the local context. Please provide details of the local review, approval or permission obtained or required. Refer to the BPG 16: Social science research conducted outside the UK. If there will be no local review, explain why not. Please mention any stakeholder or community engagement that has been/ will be undertaken in relation to the research. Please also address any physical or psychological risks for Oxford researchers and local fieldworkers in Section G.

Prior to setting up the interviews, we will make arrangements with one or more points-of-contact in-country (either affiliated with an academic or corporate institution) who will take responsibility for facilitating stakeholder engagement to identify participants who are willing and able to participate in this research. They will aid with an informal review to ensure all activities are in-line with local ethical requirements in that country or relevant institution. For the countries included in the study, it is not expected to need a visiting researchers' visa as the research is not paid for by an international university. Rather, we anticipate only needing a visitors' visa. We expect that the countries included in the study will accept the Oxford University CUREC process as sufficient clearance to conduct the research. Additionally, according to BPG 16, the project is straightforward, short-term, and unlikely to cause significant problems. Therefore, it is not feasible to obtain additional local ethics clearance in every country in the study. Most countries included in the study only require data protection assurance, which will be explained clearly in the written consent form. Thus, formal ethical review will only be undertaken through Oxford University.	
Name of departmental/ peer reviewer (if applicable)	N/A
External organisation funding the research and grant reference (if applicable)	Hilton Food Group
Please refer to the CUREC Best Practice Guidance and list any that have been used to develop your research.	Researcher Safety (BPG01) Emotional and Physical Safety Considerations: a full risk assessment will be conducted to minimize harm to both participants and researchers. Ethnographic and Other Types of Qualitative Research (BPG02) Inductive Research: This research project has been designed for the analysis phase to be flexible and adaptive, though the particulars of stakeholder participation are set and will not change. Note that this is not an ethnographic study. Informed Consent: This research will only be undertaken with informed consent by the participants with written consent before the start of the engagement. At the start of the interview recording, the researcher will confirm that they have read and understood the consent form. They will also be informed that the interview data will be kept securely and that they will not be identifiable in any research outputs. Addressing the Risk of Harm: The intent and objectives of this research will be clearly explained to the participant, and while no harms are forecasted, there will be opportunities for participants to privately express concern regarding harm. They will be given the email address of the researcher's supervisor and CUREC to report the research if necessary. There will also be the option throughout for participants to ask questions

	about the purpose of the research, where it will be disseminated, and implications of their participation. They will always have the opportunity to withdraw prior to anonymization (approximately 4 weeks after the initial interview). The researchers may also contact them in the future for clarifications should an additional study arise using the same dataset, though participants have no obligation to reply. Participant Privacy: Participants will be anonymized to the greatest extent possible, such that they are not identifiable from the data used in the analysis. Respondent Validation: Participants will be given the option to review direct quotes and the way they are reported to ensure they are comfortable that they have been sufficiently anonymized. No one will be named, and the researcher will check to ensure no one is identifiable. Elite and Expert Interviewing (BPG03) Recruiting Participants: Participants will first be informally asked to be interviewed either through our own network or our designated in-country contact. Following their agreement, they will receive a formal invitation with an informed consent form, overview of the research, and what to expect from the interview process. Written consent will be obtained well before the start of the interview process, and interview topics can be sent in advance. Data Protection: No identifiable information will be utilized from participants involved in this study. Duty of Care: The researcher has significant experience conducting elite interviews, and will mitigate power imbalances during the interview by facilitating with a clear interview question guide, and maintaining flexibility in the course of the conversation. Monitoring and Reporting: The researcher will report any adverse events which occur during an interview to their supervisor to seek advice. Management and Protection of Data (BPG09) Informed Consent: Participants will be sent a document to obtain their informed consent prior to the interview. This document will contain all necessary information regarding how data will be collected, pseudonymized, and stored.

	Anonymization and Identifiers: Individuals will be fully pseudonymized or anonymized with non-identifiable quotes which will be made clear in the gathering of their informed consent. The specific level of anonymity will be discussed and agreed upon with the participant (for example, an academic participant in Ireland may be happy to have their institution named, otherwise they would simply be described as 'an Irish academic'). The participants can request to have their data deleted at any point during the study if they so choose, until publication. Access to data: Non-anonymized interview data will only be retrievable by the research team in password-protected folders on Nexus OneDrive. No data will be shared with other participants. Data will be retained for 3 years per the University Research Data Policy, after which point it will be deleted. Special Consideration for Audio: Participants may clarify if any parts of the recording are off the record. Conducting Research Interviews (BPG10) Maximizing Benefits and Minimizing Harms: A list of topics that will be covered will be sent to participants well in advance of the interview. Participants can decline to answer any of the questions and are free to take a break at any point during the engagement session. The topics of the interviews should not bear a significant emotional burden or be too upsetting, but should the participant or researcher show any signs of distress, measures will be taken to de-escalate and re-focus the conversation to avoid emotional harm. Additionally, most expert stakeholders will have participated in similar interviews before, thus risks are lower because they will have an understanding of the process and what to expect. Accessibility: The researcher will ensure that all participants can access materials used for the interview given any potential disabilities or language needs. The interviews will occur at a venue which is convenient to the participant, so accessibility of the venue is not a concern. Note that these venues will be either corporate offices, government buildings, or university campuses, thus risks to personal safety of the researcher is minimized as all meetings will not take place at personal residences or in sparsely populated areas.

	Rights and Power Differences: The researcher will make clear that the interview is about gathering the participant's expertise and wisdom, and will confirm that the participant wishes to continue with the interview prior to beginning. Conducting Interviews Online: Should an interview take place online, the researcher will use Microsoft Teams to record the interview, and will store the data on Nexus OneDrive. Research Conducted Outside the UK (BPG 16) Local Ethics Oversight: The researcher will liaise with a contact at a university in each country who will ensure that all local ethical considerations are made, and that review from a local oversight body is obtained where necessary. In general, this project is straightforward and short-term, therefore it is not feasible or necessary to obtain full ethical clearance from each country included in the study.

Section D: Recruitment of research participants		
Number of participants	30-50 (approx.)	
How was the number of participants decided?	We aim to interview a large enough number to get multiple perspectives from each stakeholder group and nationality, but likely not more than 50 due to limited size of participant pool and number of relevant experts.	
Age range of participants	18 and over	
Inclusion criteria	Relevant expertise Publicized position on the topic Conducting research on the topic Engaged in policy discussions around agricultural mitigation	
Exclusion criteria	Not from one of the countries within the scope Insufficient background knowledge	
Indicate with an 'X' all intended recruitment methods Please submit copies of the recruitment material that will be used, e.g. advertisement text, introductory email text.	Poster advert	☐
	Flyer	☐
	Email circulation	☐
	Social media (e.g. Twitter, Facebook)	☐
	Website	☐
	In-person approach	☒
	Snowball sampling	☒

	Recruitment sites (e.g. Mechanical Turk)	☐
	Existing contacts or volunteer database	☐
	Other (please specify):	☐
How will potential participants be identified and approached?	Participants will be identified either through the research team's own networks, or through the designated points-of-contact for each country. For countries and/or stakeholder groups where our networks are more limited, we will use snowball sampling to identify a wider range of potential interviewees. Participants will be approached either by the research team themselves, the funder, or by the point-of-contact (with the research team copied) to make an introduction. Participants will first be asked informally if they are willing to be interviewed, and will be given some high-level information about the study and interview process at that time. Once they have agreed to participate, the researcher will send the consent form.	
Will informed consent be obtained from the research participants or their parents/ guardians? If not, please explain why not.	Yes, informed written and/or verbal consent will be obtained from participants	
For each activity or group of participants, explain how informed consent will be obtained from the participants themselves and/ or their parents/ guardians, if applicable. How will their consent be recorded? Please submit copies of all participant-facing materials for review. E.g.: Recruitment material (e.g. emails, posters) Information for participants to read (or hear) before they agree to take part (e.g. written information or, if applicable, an outline oral information script). A document to record informed consent. Further guidance and templates.	Informed consent will be obtained through a written or digital signature after participants have read informational material around the purposes of the study, the nature of the interview, and the protection of personal anonymity and data. The researcher will also confirm consent verbally at the start of the interview. All interviews will be conducted in English, and we do not expect to require any translations. Appendix 2 contains all participant-facing materials, including a recruitment letter and consent form.	
Provide details of any payments and incentives and the rationale for providing these. Further guidance in Best Practice Guidance: 05 Payments and incentives in research.	None	
Describe how participants may withdraw from the study may withdraw any personal information they have provided from the study	Participants may withdraw from the study up until data is anonymized (approximately 4 weeks after the initial interview) by notifying the researcher over email or phone call. Following initial anonymization, participants may withdraw data	

State any limits to withdrawal, for example once the data has been anonymised or at some other specified stage prior to publication. Make sure participants are aware of any withdrawal limits.	for use in any further studies. Participants will be made aware of this timeline at the time of the interview.

Section E: Research data			
All information provided by participants is considered research data for the purpose of this form. Any research data from which participants can be identified is known as personal data; any personal data which is sensitive is considered special category data. Management of personal data, either directly or via a third party, must comply with the requirements of the UK General Data Protection Regulation (UK GDPR) and the Data Protection Act 2018, as set out in the University's Guidance on Data Protection and Research. In answering the questions below, please also consider the points raised in the Data Protection Checklist and Data Protection Screening Assessment and whether, for higher-risk data processing, a separate Data Protection Impact Assessment may also be required for the research. Advice on research data management and security is available from Research Data Oxford and your local IT department. Advice on data protection is available from the Information Compliance team. For guidance on conducting internet-mediated research, refer to CUREC's Best Practice Guidance 06: Internet-mediated research.			
What data will be collected? (Indicate with an 'X')			
Screening documents	☐	Task results (e.g. questionnaires, diaries)	☒
Consent records (e.g., written consent forms, audio-recorded consent, assent forms)	☒	IP addresses (refer to Best Practice Guidance 09: Data collection, protection and management for guidance)	☐
Contact details for the purpose of this research only	☐	Field notes	☐
Contact details for future use (guidance)	☐	Photographs	☐
Opt-out forms	☐	Information about the health of the participant (including mental health)	☐
Audio recordings	☒	Previously collected (secondary) data	☐
Video recordings	☐	Data already in the public domain. Specify the source of the data:	☐
Transcript of audio/ video recordings	☒	Other, please specify:	☐

During the course of the research, where will each type of research data be stored?	Consent forms with participant contact details will be kept in a password-protected Nexus OneDrive account accessible only by the researchers. The audio recordings will be temporarily stored on an audio recording device loaned by the department until the recording can be transferred to OneDrive, at which point it will be deleted off of the device. The audio data and any non-anonymous interview notes will be stored in OneDrive for three years, after which point it will be destroyed. Due to the sensitive nature of this data, and the fact that the stakeholders are experts, the full transcripts will not be publicly archived.		
Who will have access to the research data during the project?	The researcher's supervisors, Myles Allen, Emily Cox, and Harriet Bartlett, are the only additional individuals who will have access to the non-anonymized data throughout the project.		
Please complete this section if your research involves the use of secondary (i.e. previously collected) data.	Please indicated with an 'X'.	Yes	No
	Are data access agreements in place for access to and use of this secondary data? (If so, please attach these.)	☐	☐
	Did the individuals agree that their data could be used for this purpose?	☐	☐
	Could anyone (including members of the research team) link the data back to an individual or individuals? If this is a possibility, please explain how the associated ethical issues will be addressed:	☐	☐
How do you intend to share the research data at the end of the project?	Depositing in a specialist data centre or archive	☐	
	Submitting to a journal to support a publication	☐	
	Depositing in an institutional repository	☐	
	Dissemination via a project or institutional website	☐	
	No plans to share the data	☒	
	Other (please specify):	☐	
How do you intend to report and disseminate the results of the research? (Indicate with an 'X')	Thesis publication	☒	
	Publication in a peer reviewed journal	☒	
	Publicly available report	☐	
	Conference presentation	☒	
	Publication on a website	☐	
	Pre-registration	☐	
	Report to a research funder	☒	

	Providing participants with a lay summary of the results	☒
	Submission for academic assessment	☒
	Other (please specify):	☐

Explain what will happen to the data at the end of the research project. This question must be answered for each type of data, including completed consent forms.
The consent forms, interview notes, and audio recordings used for the study will be deleted off of OneDrive no later than three years after the conclusion of the study. If the primary researcher should leave the university before the conclusion of the three years, the data will be securely transferred to one of the co-authors to store until the end of the three years.

Section F: Protection of research participants and their personal data		
How identifiable will the participants be from the **research outputs**? (Indicate with an 'X')	Directly identifiable from the information included	☐
	Pseudonymised/ indirectly identifiable	☐
	Not identifiable – data is anonymous	☒
	Other, please specify:	☐
To what extent will the data be de-identified? How identifiable will any individuals be from the research data? Describe any measures you will take towards assuring confidentiality, potential risks to confidentiality.	In the process of setting up the interview, the researcher and participant will work together to decide the extent to which the participant will be anonymized to be aligned with the requirements of their occupation. All participants will be anonymized to the degree of the participant with the most stringent anonymity requirements in order to maintain uniformity across descriptions of participants. To minimize any risks to confidentiality, the researchers will not share the identities of participants with any third-parties, and the pseudonyms used will be chosen such that they would not reveal the participant's identity.	
How will you ensure that third parties (e.g., interpreters and transcribers) are aware of and adhere to the measures described in this form?	No third parties will be involved	

Section G: Risks and benefits of the research
Will the research involve topics that could be considered sensitive? If so: Please provide more detail or supporting information (such as the interview questions) to show the range of questions; Explain what steps will be taken to reduce risk of distress;

Consider seeking advice from within your Department or from the ethics committee including whether the application might benefit from additional ethics review (e.g., via a CUREC 2 application).
Research topics are not considered sensitive.
Describe any additional burden or risks to the participants and the steps you will take to address these.
Interview fatigue is a potential burden for research participants, particularly when they are asked to be involved in multiple studies in a short amount of time. Because participation is fully optional, participants would be able to opt out at any time should they become inundated with interview requests. While the topic and nature of the interview is not sensitive in such a way that participants' opinions could be seen as controversial, we recognize that many participants will want to be as anonymous as possible to avoid any issues with their employer or institutional affiliations. To mitigate this risk, the researcher will confirm that they are comfortable with the level of pseudonymization used to describe their affiliation, and if an agreement cannot be reached, they will be reminded of their option to withdraw.
Describe any physical or psychological risks to the researcher(s) (including local fieldworkers or research assistants) and the steps you will take to address these.
Most interviews will take place either in academic, corporate, or government buildings where physical risk is low or non-existent. For interviews taking place with farmers/on farms, the researcher will be accompanied by a trusted in-country partner who will facilitate setting up the interviews so the researcher will not have to travel alone. The primary physical risk during the field work is from driving between meeting locations. All necessary precautions will be taken while driving such as wearing a seatbelt and following local road laws. The topics of the interviews are not distressing or emotionally burdensome, thus psychological risks to the researchers is believed to be minimal. However, doing multiple interviews in a short period of time can be exhausting for the researcher, so we will avoid scheduling more than two interviews per day in order to prevent burnout.
Describe any benefits of the research, both to participants and to others.
Participants will be contributing to research which is both timely and practical given the ongoing pressures for countries and companies alike to develop science-informed climate mitigation targets. This research will inform those bodies of how they might approach the quantification of agricultural impact in a novel way. At the very least, the analysis will provide insight into how various stakeholder groups conceptualize climate mitigation in the land sector to facilitate better collaboration and communication across the food supply chain and policy space. Stakeholders will be informed about the progress of publications resulting from this study or any tangible impacts the research has had. The research teams will also make themselves available to facilitate discussions with individual participants on how to use the knowledge generated from the analysis in their own lines of work.
Give details of any other ethical issues or relevant information.

N/A

Section H: Professional guidelines		
Please indicate with an 'X' at least one set of professional guidelines you will follow.		
Research specialism/ methodology	Association and guidance	
Anthropology	Association of Social Anthropologists of the UK	☐
Computer Science	ACM Code of Ethics and Professional Conduct	☐
Criminology	British Society of Criminology Statement of Ethics	☐
Education	British Educational Research Association Ethical Guidelines for Educational Research	☐
Geography	American Association of Geographers Statement on Professional Ethics	☒
History	Oral History Society of the UK Ethical Guidelines	☐
Internet-mediated research	Association of Internet Researchers Ethical Guidelines British Psychological Society: Ethics Guidelines for internet-mediated research Association for Computing Machinery Code of Ethics and Professional Conduct	☐
Management	Academy of Management Code of Ethics	☐
Political Science	American Political Science Association (APSA) Guide to Professional Ethics in Political Science	☐
Politics	Political Studies Association. Guidelines for Good Professional Conduct	☐
Psychology	British Psychological Society Code of Ethics and Conduct	☐
Social research	Social Research Association: Ethical Guidelines	☐
Socio-legal studies	Socio-Legal Studies Association: Statement of Principles of Ethical Research Practice	☐
Sociology	The British Sociological Association: Statement of Ethical Practice	☐
Visual research	ESRC National Centre for Research Methods Review Paper: Visual Ethics: Ethical Issues in Visual Research	☐
Other professional guidelines	List any other guidelines used here.	☐

Section I: Endorsements and signatures
Please ensure this form is endorsed by the Principal Investigator (or student's supervisor), the Head of Department (or nominee) and, if student research, by the student themselves.

The SSH IDREC Secretariat accepts either option below. If you have a **DREC**, check which signature option it prefers.
Option 1: direct email endorsements
Each of the signatories should submit an email from a University of Oxford email address, indicating their acceptance of the responsibilities listed below.
Option 2: signatures
Please scan the signed form and email it to us as a PDF. Pasted images of signatures cannot be accepted.

Endorsement by the Principal Investigator/ student supervisor and student, if applicable

I/ we the researchers understand my/ our responsibilities as Principal Investigator (and student, if applicable) as outlined in the guidance on the CUREC website. I/ we declare that the answers above accurately describe the research as presently designed, and that the ethics committee will be informed of any changes to the project which affect the answers to this form.
I/ we will inform the relevant IDREC if the Principal Investigator changes.

Name of Principal Investigator	Professor Myles Allen
Principal Investigator's signature	
Date	27 November 2024
Name of student (if applicable)	Jessica Zionts
Student's signature	
Date	27 November 2024

PARTICIPANT INFORMATION AND CONSENT FORM

Central University Research Ethics Committee Approval **SOGE C1A 24 127**

Context

Currently, different stakeholder groups and national policies around the world operate on different assumptions about how to measure and mitigate the impact of agricultural production. These discrepancies result in disjointed efforts and can cultivate perverse incentives. Thus, there is a need to understand the origins of these different assumptions to attempt to create a more unified vision of a sustainable food future, and to better delineate the roles that government, industry, and farmers can play.

The primary aim of this study is to map stakeholder definitions of climate neutrality and conceptualizations of sustainability in the livestock sector. In line with this aim, we ask the question; how do definitions of climate neutrality in the agriculture sector differ across stakeholder groups and geographies? Are these definitions influenced by what mitigation opportunities are available for a given stakeholder?

To do this, we will analyze themes, similarities, and differences across stakeholder perspectives to determine whether it's possible to establish a unified definition for the climate neutrality of livestock. Underpinning these objectives is a more philosophical question about whether the concept of climate neutrality should be relevant at all to the livestock sector or agriculture as a whole. Unlike fossil fuels, which have zero-carbon alternatives, agriculture will never be free of environmental impacts whether that's on climate, land use, biodiversity, or water use. Despite this, humans will always need agriculture. Given this reality, is 'climate neutrality' an appropriate goal to begin with? Or should we seek out an alternative paradigm?

Q&A

Why have I been asked to take part?

You have been invited due to your role as a policymaker, corporate stakeholder, interest group member, or academic with relevant expertise and experience in the area of agricultural emissions accounting and mitigation.

Is participation in this study mandatory?

Participation in this study is fully voluntary. Should you choose to participate, you may withdraw any unprocessed data at any time. The deadline to withdraw data will be communicated based on the date of the interview.

What is involved should I choose to participate?

Participation in this research will involve an interview of approximately one hour either in-person or via Microsoft Teams. These interviews will be audio-recorded and semi-structured. You may ask to pause or stop the interview at any time.

Your data will be fully-anonymized and you will not be recognizable in any publication.

Are there any disadvantages or risks to participating in this research?

There are no anticipated risks of participation. You may choose to refrain from answering any question at your own discretion.

Are there any benefits from participating in this research?

While this research is not compensated, nor are there any other direct benefits to participation, your contributions will enrich the data used to generate insights into how we can develop more effective mitigation targets and strategies in the agriculture sector. The knowledge generated from this study aims to guide work done across the stakeholder groups included, meaning there will be useful outcomes for all who choose to participate. By understanding how other groups perceive the same challenges, we hope this analysis can facilitate more coordinated efforts across the land sector and supply chains.

Who will have access to the data?

Your non-anonymized data will be accessible by the research team involved with this study (Jessica Zionts, Dr. Myles Allen, and Dr. Harriet Bartlett) The University of Oxford is the data controller with respect to your personal data, and as such will determine how your personal data is used in the study. The University will process your personal data for the purpose of the research outlined above. Research is a task that is performed in the public interest. Further information about your rights with respect to your personal data is available at https://compliance.admin.ox.ac.uk/individual-rights

Contacts

Should you have any concerns before or after the interview, you may reach out to the Principal Investigator or Co-Investigator.

Myles Allen- Principal Investigator
Myles.allen@ouce.ox.ac.uk

Jessica Zionts- Co-Investigator
Jessica.Zionts@ouce.ox.ac.uk

Consent Form

Please initial each box if you agree

I confirm that I have read and understand the information sheet for the above research. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	☐
I understand that my participation is voluntary and I may withdraw any un-processed data at any time.	☐
I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.	☐
I understand that I will not be identifiable in any publications.	☐
I consent to being audio recorded and understand how the recordings will be used, and I understand that data obtained in the workshop may be utilised in discussion with other researchers and in any ensuing presentations, reports or publications.	☐
I give you permission to clarify any information.	☐
I understand how to raise a concern.	☐
I consent to participate.	☐

I, (PRINT NAME) _______________, consent to participate in this study conducted by Jessica Zionts at the School of Geography & Environment, University of Oxford

Sign:

Date:

Interview Outline

1. Tell me a little about your professional background.
    a. How did you come to be in this area of expertise?
    b. What motivates you in this role?
2. What do you think the priorities of animal agriculture are?
    a. What role do you play in your country's food system
    b. What role does your country play in the global food system?
    c. How do you interact with:
        i. Policy makers
        ii. Farmers
        iii. Corporate entities
        iv. Researchers?
    d. Who sets these priorities?
3. Is your country a net importer or exporter of animal products?
    a. Do you think this is a good thing?
    b. How do you value domestic food security relative to feeding populations elsewhere?
    c. How do you balance local sustainability with global trade demands?
4. What are your thoughts on the environmental impacts of agriculture?
    a. Do you agree with national policies around mitigation?
    b. If no, what would you change?
    c. How do you think other stakeholders define it?
    d. What are your thoughts around livestock-specific impacts like methane or land use?
5. What is your country's objective in climate mitigation for agriculture?
    a. Do you agree with that objective?
    b. What does it mean for you?
    c. How achievable do you think these objectives are?
    d. Who do you see as the winners and losers?
6. How do you feel about national strategies that

a. involve shifting diets and reducing food waste
b. taking land out of agricultural production
c. prioritizing domestic biodiversity
d. prioritize removals
e. Is there dialogue around shifting farm types?
f. Do you see resistance around these strategies? How would they impact you?

7. Are you aware of how your country and/or company measure the environmental impact of agriculture?
    a. Do you think this is a good approach?
    b. Is there anything that maybe isn’t counted or appropriately valued?
8. Is there anything else you think is important in understanding the meaning of net zero livestock?

Appendix IV

The following text will be submitted as a preamble to the reflections in Chapter 2.3.7 as a Perspective in *Nature Climate Change:*

As companies and governments alike set net zero targets and develop strategies to mitigate their environmental impacts, it is crucial that the choices around how these impacts are measured are not overlooked. To make these judgements effectively, metrics must be understood based on what they are and, perhaps more importantly, are not measuring. This perspective traces the origins of novel and conventional greenhouse gas (GHG) and land use metrics, and discusses their various applications on the basis of their usefulness in developing effective climate policy. Ultimately, we argue that decisions around target-setting and metric choice must be made with the goal to reduce emissions as ambitiously as possible, as opposed to choosing accounting conventions that make modest mitigation appear ambitious.

GHG Metrics

The Kyoto Protocol considers seven gasses to be GHGs: CO_2, CH_4, N_2O, HFC, PFC, SF_6, and NF_3. The average lifespans in the atmosphere of each gas vary widely. CH_4 lasts merely 11.8 years while N_2O lasts 109 years (IPCC 2021b) and trace amounts of CO_2 can still be present in the atmosphere after 100,000 years (Lord et al. 2016). As a result, their impact on the climate, typically measured based on radiative forcing, are quite different. Because the Kyoto Protocol required parties to implement policies to reduce all of these gases, there became a need to create a metric whereby the different gases could be compared against each other (Jan S. Fuglestvedt et al. 2003). The Global Warming Potential (GWP) was introduced in 1988 as a way to normalize the harmful effects of the different gases into a single metric (S. J. Smith and Wigley 2000).

Specifically, GWP is a ratio of the integral of the radiative forcing over a specific time period of a GHG divided by the integral of the radiative forcing of CO_2 over the same time interval (Harvey 1993). The method was adopted from the calculation of ozone depletion potential (ODP), where each GHG was normalized against a well-known benchmark over a specific time interval (WMO 1991).

The choice of time interval for GWP, normally between 20, 100, and 500 years, is a policy choice, not a scientific result (Fearnside 2002a). Shorter time horizons are equivalent to high discount rate scenarios, where short-term impacts are weighted more heavily. Conversely, longer time horizons are equivalent to a very low discount rate, which assumes there is no benefit from acting earlier as the effects of today will transfer into future generations. As a result, investments to manage and mitigate gases will depend on which gas has a higher time-preference weight.

The 100-year time horizon was picked by the Intergovernmental Panel on Climate Change (IPCC). It is functionally equivalent to a discount rate of 0.9% (Fearnside 2002a). An advantage of the 100-year interval is that it is aligned with the time in which decision makers can still have direct contact with the living future population, as one's grandchildren and great-grandchildren will likely be alive within that time interval (Fearnside 2002b). In other words, it is long enough for one to make inter-generational choices but not too long where the future becomes an abstract concept. However, the 100-year time horizon is significantly longer than the lifetime of methane and other short-term gases. As a result, the damage caused by short-term GHGs are underweighted.

In 2016, a new metric called GWP* was developed in response to the critiques around the inability of GWP_{100} to accurately represent the short-lived properties of methane (Allen et al. 2016, 2018; Cain et al. 2019). Rather than comparing the radiative forcing of different GHGs over a given time horizon, the GWP* calculation is based on the *rate of change* of methane over a 20-year sliding window. Considering methane in this way yields results, which better reflect the impact of emissions on future temperature. Thus, the units of measurement are tonnes of CO_2-warming equivalent emissions, as opposed to GWP_{100}'s CO_2-equivalent emissions.

When applied to annual inventories of countries or regions with stable or slightly declining methane emissions, such as California whose methane emissions increased in the past with the expansion of dairy farming, methane appears to contribute very little to the state's current climate impact (Mitloehner et al. 2020). This effect of "grandfathering" in historical emissions has been fairly criticized (Cusworth et al. 2023; Carter and Urbancic 2023). However, as we discuss in the following pages, there is an application of GWP* that can facilitate the development of strategies to minimize further warming. When used in forward-looking consequential accounting, GWP* rewards reductions in methane more than GWP_{100}. To effectively leverage this benefit, GWP* should not be used in an inventory accounting framework, which leads to the aforementioned perverse incentives. However, understanding the impact of a decision on future temperature is valuable information, which GWP* provides.

Land Use Metrics

In national emissions accounting, emissions from land use change are calculated based on land cover changes that happen each year. In corporate emissions accounting, however, the calculus is dependent on the quality of the data transferred down the supply chain. Statistical land use change (sLUC) is the conventional mechanism for allocating land use change (LUC) emissions to commodities. It is calculated as the annualized emissions associated with the clearing of land for agriculture over the past 20 years (WRI and WBCSD 2022a). It can be calculated based on *product expansion*, where emissions are only allocated to products sourced directly from recently-deforested land. However, this requires data at a high spatial resolution that is not typically available. Usually, sLUC is calculated using the *shared responsibility* method, where country-level LUC emissions are allocated to all products from that country.

sLUC was developed to indicate the amount of deforestation linked to a company's supply chain (Ponsioen and Blonk 2012). However, to eliminate sLUC emissions, a company can simply shift its suppliers such that no materials are purchased from countries with recent deforestation. For example, one company sources one tonne of soy from Brazil and another company sources the same amount from the United States, the former would report high sLUC emissions, while the latter country would report none. The choice of a 20-year time horizon has been criticized as being subjective, yet substantially influential in how it impacts decision-making (Maciel et al. 2022). The consideration of time in this calculation ignores that deforestation for soy continues because of increases in global demand. Therefore, we argue that the allocation of "blame" for LUC according to source is not conducive to halting deforestation at the global level, and is a direct result of the assumptions made by the sLUC calculation.

The Carbon Opportunity Cost (COC) was developed in 2018 in response to this idea that LUC emissions do not occur because of the origin of land-based products, but rather because of global demands driving competition for land use (Searchinger et al. 2018). This metric indicates the contribution of a given land-based product to the depletion of the biosphere's carbon stocks at a global level. The difference between historical and current carbon stocks on all land where a product is grown is allocated equally to each tonne of that product.

This more complex calculation allocates "blame" to land-based products based on the difference between a piece of land's potential carbon storage and agricultural productivity. Therefore, no land use is treated as "free," and inclusion of the COC incentivizes mitigation interventions that would have otherwise been overlooked (Zionts et al. 2025). The COC can be reduced on the production side by improving agricultural efficiency such as increased yields. On the consumption side, the COC can be reduced by shifting towards less land-intensive products, such as from beef to plant-based proteins. The native potential vegetation data used in the COC calculation has been criticized on the grounds that biogenic carbon stocks are dynamic and stochastic, thus efforts to estimate them are inherently uncertain (Chiarucci et al. 2010).

The annualization method used in the COC calculation has generated further criticism, though these critiques are not published in the literature. The COC uses a calculation resembling discount rates used in economic decision making on the grounds that *"carbon storage is lost quickly but crop production can continue indefinitely"* (Searchinger et al. 2018). Thus, the discount rate allows the impacts of clearing land to be allocated over some period, similar to the 20-year allocation period used for dLUC. Specifically, the COC calculation applies a 4% discount rate, which is higher than the 3% rate typically applied in mitigation valuation (Nordhaus 2017). Searchinger et al. (2018) justify their choice of discount rate based on the idea that a higher discount rate incentivizes more rapid near-term mitigation (Gerlagh and van der Zwaan 2004; Schoenmaker and Schramade 2024). The discount rate is ultimately a policy choice, and the authors note that COCs can be calculated with different rates, but it would not significantly influence decision-making in the case of this calculation.